5  Small Cells and HetNet Deployment ................................................................. 71
6  Miscellaneous Commercial and Deployment Issues ......................................... 75
   6.1  Constraints on the Antenna Deployments due to Commercial Considerations 75
   6.2  Electrical and Mechanical Tilting of Antennas ........................................... 76
   6.3  Passive Intermodulation (PIM) Site Considerations ....................................... 90
   6.4  Independent Antenna Tilt Optimization by Air Interface ............................... 91
   6.5  Remote Radio Heads for MIMO ................................................................. 92
   6.6  Cable Tradeoffs for Remote Radio Heads ................................................... 96
   6.7  Co-Siting of Multiple Base Stations and Technologies ............................... 103
   6.8  Indoor Distributed Antenna System — MIMO Coverage ............................ 115
7  Terminal Antennas ............................................................................................. 117
   7.1  Prospects and Characteristics of Multiple Antennas in Terminals ............... 117
   7.2  UE Performance at 750 MHz with MIMO ................................................... 121
   7.3  Current Status of terminal antennas .......................................................... 125
Definitions and Acronymns .................................................................................. 128
References ............................................................................................................ 133
Acknowledgements .............................................................................................. 138
SUMMARY

In 2010 this organization, then called 3G Americas, published the first version of this whitepaper on antennas. At the time, only simulations and very early trials of LTE were available. Since then, along with the terrific growth in smart phones and wireless data traffic, the industry has seen important changes to the types and methods of deploying wireless systems. Wireless coverage is no longer the driving force for deployment; capacity is. The need to double capacity each year has resulted in the major push for LTE, the deployment of 3G Small cells, HET-NETs with WiFi, and residential cellular base stations. Some operators have deployed 4 branch antenna systems and Remote Radio Heads/Units have become common. Increasingly, operators are integrating more active electronics on tower tops and even inside the antenna radomes. Active antenna arrays capable of vertical sectorization are in trials, and LTE-Advanced standards have been finalized and it has been in lab trials with deployments being planned.

In short, the wireless landscape has changed in the past two years and it is time for a refresh of this document.

INTRODUCTION

The extraordinary growth in wireless data traffic is putting immense strain on the operator’s network. To address this demand and increase capacity, operators have five primary tools at their disposal:

1) Adding Cell Sites is an effective but expensive approach to adding capacity. In general adding new real estate is time consuming and increasingly prohibitive. With median inter-site distances dropping from 5km to 2km and recently to less than 200m in dense urban areas, the operator has less choice in selecting affordable property. Doubling the number of cell sites approximately doubles the network capacity and the throughput per user (assuming the user density stays constant), and greatly improves the peak user and the aggregate throughput per km2.

2) Adding sectors, such as changing from 3 sectors to 6 sectors, is a useful way to approximate the introduction of new cells. However, this does not quite double the capacity as the “petals” of 6 sector coverage do not interleave as well as 3 sector coverage, and the fractional overlap of 6 sectors is greater. This also challenges handoff processing when near highways. This is a common approach in dense urban areas where rooftops are available. There is about a 70% increase in capacity in moving from 3 to 6 sectors in an environment with low angle spread (where the base station is located above the clutter).

3) Adding Carriers (or more accurately, bandwidth) directly adds to capacity. The LTE standard is particularly adept at utilizing increased bandwidth. In addition, in the USA, the FCC permits increasing radiated power with the bandwidth in the PCS, AWS, and lower 700 MHz bands providing improved penetration and coverage. Doubling bandwidth at least doubles throughput.

4) Improved air interface capabilities, such as in evolving from R99 UMTS to Release 5 HSDPA, provided well over 4 times the aggregate downlink capacity for example. However, in moving from, say, Release 6 HSPA (1x2) to Release 7 (1x2) with 64QAM and 2x2 MIMO we see a more modest ~10-20% improvement in the aggregate throughput. As has been observed before, with improvements in air interface (while leaving everything else the same such as bandwidth and antenna configuration) we are seeing diminishing returns on improvements. It is clear that something more than simply increasing modulation and coding rates is needed.
5) Smart antennas provide the next substantial increase in throughput. The peak data rates tend to be proportional to the number of send and receive antennas, so 4x4 MIMO is capable of serving twice the peak data rates as 2x2 MIMO systems.

We’ve witnessed an important trend in the nearly 3 decades of wireless system growth, shown in Figure 1 below. On a log plot we see the rather steady growth of the number of macrocell sites in the United States. We see a very steady growth of about 30% year over year from 1986 through about 2002, but since then the growth rate has decreased to about 2% since 2005. We interpret these trends as corresponding to a coverage growth phase and a more recent phase where the number of sites has not grown much but the capacity of the sites have been greatly expanded. More carriers, more bands, and more capable air interfaces have been deployed at these more intensely active base stations.

![Number of MacroCells from CTIA semiannual report Dec. 2011](image)

**Figure 1** – The number of macrocells deployed in the United States. Source of data: CTIA Semi-Annual Reports.¹

This “intensification” of the existing cell sites has involved deploying multi-band antennas and remote radio heads adjacent to the antennas, as well as having more carriers with their associated power

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¹ These are reported by the CTIA as “cells” referring to the number of independent base station sites deployed by the various operators. A single tower may have as many cells as there are operators collocated at the tower. Our understanding is that these sites do not include femtocells or indoor sites that are not inventoried by the operators.
supplies and baseband processing facilities located at these sites. In general, the sites have evolved
to more capable and “smarter” equipment, including smarter antennas.

By “smart antennas” we refer here to adaptive antennas such as those with electrical tilt, beam width,
and azimuth control which can follow relatively slow-varying traffic patterns, as well as so called
intelligent antennas that can form beams aimed at particular users or steer nulls to reduce interference
and Multiple-Input-Multiple Output (MIMO) antenna schemes. Finally, we also consider adaptive
antenna arrays with the ability to apply separate signals to antenna elements in both the vertical and
horizontal axes to form beams or sectors in the vertical plane, as well as implement MIMO and receive
diversity with elements on the other axis.

A goal of this paper is to focus attention on the practical aspects of deploying smart antenna systems
in Radio Access Systems (RAS). Additionally, networks are increasingly using small cells and base
stations deployed indoors or below the clutter where the experience gained from decades of tower
mounted antennas do not apply. This paper also addresses the practical aspects of deploying these
modern base stations with their increasingly capable antennas.

A substantial body of theoretical and field experience is able to provide reliable guidance in the
tradeoffs of various antenna configurations. Operational experiences with commercial LTE wireless
systems have demonstrated many of these gains and their practical deployment issues. Several
previous papers describe the theoretical capabilities of smart antennas and the mechanisms that
provide for their support in the standards. The reader is referred to surveys such as those in various
recent publications.

Section 2.2 of this paper gives the basics of LTE downlink MIMO schemes. Section 1.1 covers the
evolution of the base station antenna. Section 2.2 describes MIMO antennas and their operation.
Section 1.4 gives an overview of Active Antenna Systems and summarizes current performance
expectations. A good portion of this paper comes from a 4G Americas Whitepaper on the general
subject of MIMO and Smart Antennas published in May 2010 that the reader is referred to for further
background.

1 ANTENNA FUNDAMENTALS

Antennas are critical to all wireless communications and significant advances in their capabilities have
been made in the past several decades. Figure 2 below shows the inside of a modern antenna, where
we are reminded that what we refer to as an antenna consists of a number of individual antenna
elements all contained within a single radomes. The antenna shown below has four coaxial DIN†
connectors serving two frequency bands each with two polarizations. The coaxial connections feed a
distribution network that connects the 4 separate signals to the radiating elements. In one case, the
coaxial connector feeds the +45° polarization of the 5 higher frequency band radiating elements
mounted on the circular plates) while another coaxial connection feeds the +45° polarization radiating
elements in the 4 lower frequency band radiating elements. The feed network includes a variable
phase shifter shown in Figure 3 that introduces a larger transmission delay to the lower elements so
that the electromagnetic waves radiating from the elements will be in phase at an angle tilted down

† Coaxial RF connectors standardized by the Deutsches Institut für Normung (DIN).
toward the ground where the mobile users are located. The tilt angle may be adjusted with a manual tilt rod or a motorized actuator controlled remotely over the AISG connection.

We see in this structure a total of 18 radiating antenna elements; 5 high band at +45° and at -45°, and 4 low band of each polarization. When packaged in a common radome we refer to this overall structure as a single antenna even though there are these 18 antenna elements inside. We refer to this as a single cross polarized column with two frequency bands interspersed. Also, even though the tilt actuator is motorized, we refer to this as a passive antenna because there are no active elements in the signal paths. (Active electronics use DC power to amplify or transform signals.) We will see in section 1.3 that there are emerging new Active Antennas (AA) with active electronics in the radome as well.

Generally, the taller an antenna is, and the more elements there are in a column, the more resolution we have in shaping the vertical characteristics of the radiated pattern. That is to say, doubling the height allows us to about halve the vertical beam width and about double the antenna gain. This is tied to the wavelength so as the frequency doubles with a fixed height radome, we also tend to be able to double the antenna gain and halve the vertical beam width.

Consequently, in many installations where the antennas are limited to a fixed height such as 6 feet for esthetic and zoning reasons, we see that the higher frequency bands can have twice the antenna gain (3dB) as the lower frequency bands.
Likewise, the antenna width impacts the horizontal beam width. This is why a six sectored installation requires antennas that are about double the width of three sectored installations.

More detailed definitions and acronyms concerning antennas are listed in the Appendix.

![Figure 3](image-url) – View of the back of a typical modern antenna showing the tilt mechanisms.

Base station antenna technology has progressed in response to industry requirements and trends. The key drivers have been the continuing addition of cellular frequency bands, the integration of more functionality into single radome housing, and antenna techniques that contribute additional capacity to cellular networks. The following figures concisely describe the development of the base station antenna including advanced antenna technologies in use and emerging today.

### 1.1 BASE STATION ANTENNA TYPES AND EVOLUTION

The early days of commercial cellular communications was deployed primarily through omni-directional antennas. These “Omni” antennas are typically linear cylinders, resembling a pipe. They generally radiate in all azimuth directions, hence the name “omni-directional”. Omni antennas provide low capacity when compared to more current technologies. For receive spatial diversity, the antennas are normally spaced $10\lambda$ apart. Refer to Figure 4.

The second season of base station antenna technology introduced the first “panel” antennas. These antennas were packaged in wider housings, supported with brackets on the back surface. They offered some beam control and were commonly vertically polarized. Azimuth beamwidth could now be controlled, providing cell sector handoff capability. With defined elevation beamwidth, site coverage
could then be tailored using mechanical downtilting through the mounting brackets. These are also shown in Figure 4.

The next evolution step was the inclusion of log periodic dipole antenna elements. These radiating element arrays offered improved directivity. This improved beam control resulting in better sector handoffs and reduced interference. Again, refer to Figure 4.

Two very significant advancements came next in base station antenna technology. Dual-polarized antenna arrays were invented. In this advancement, a combined element array using polarization diversity provided two ports to be combined in a single antenna. The elements used 45° slant polarization, with the second polarization rotated 90°. These dual-polarized antennas replaced two spatial diversity vertical polarized antennas. The second key development in this phase was electrical tilt of the antenna beam. Phase controlled tilt utilized new technology to tilt the beam, providing some coverage control without the distortion effects found with mechanical tilting. See Figure 5.

Next came variable tilt antennas and Remote Electrical Tilt (known as RET). This technology utilized phase shifting devices inside the antenna to more precisely control the beam tilt. With this design, the phase shifters could be coupled to motorized actuation systems with remote control capabilities. This allowed downtilt control and cell coverage optimization from remote sites without climbing towers. See Figure 5.

The next significant development was dual-band antennas. These antennas combined two different frequency band antennas into a single housing. This again reduced the required antennas by 50%,
reducing leasing costs and increasing tower space efficiency. Each frequency band had capability for independent RET controls. A further advancement included three frequency bands in a single housing. See Figure 5.

A more recent development is a line of antennas intended for 6-sector cell site configurations. These antennas feature azimuth beamwidths of 33 or 45 degrees. The 3-sector arrangements typically use 65, 85, or 90 degree beamwidths. The 6-sector arrangements offer increased antenna ports and therefore increased capacity capability. These are shown in Figure 6.

A further refinement of 6-sector antenna solutions incorporates multiple beams in a single housing. A common twin-beam version incorporates two 38 degree beams in a single housing. This is another development to increase coverage and capacity without additional antenna housings on the tower. Refer to Figure 6.

Another antenna trend is concealment or integrated housings. In these designs, the antennas may be housed in a structure which is disguised. Many of these include 3-sectors and may also include tower mounted amplifiers, remote radio units, or other peripheral devices inside the housing. One example is shown in Figure 6.
Typical antennas being deployed today have 2 or 4 cross polarized columns of antenna elements (±45° polarization) to provide 2 or 4 branches per frequency band. Variable electromechanically tilted Remote Electrical Tilt (RET) is generally available and increasingly deployed with a tilt range of 0 to 10° (though sometimes with as much as 18°.) While most existing antennas are single band, multiband antennas are increasingly used (when Passive Intermodulation concerns and diplexer losses permit). Elevation beamwidths range from 8 to 16°, and horizontal beamwidths vary between 33° and 90° with 65° being most common (75%).

At the risk of stating the obvious, it may be worth pointing out that beamwidths vary inversely with the size of the antenna aperture. For example, a radome that is twice as tall can generate a vertical beamwidth that is twice as narrow and with about twice the gain (+3dB). Antennas with horizontal beamwidths for 6 sectored base stations with horizontal beamwidths of around 35° are typically about twice as wide as antennas in the same band with 65° horizontal beamwidths, and the narrower beamwidth has the higher peak gain.

1.2 RECONFIGURABLE BEAM ANTENNA

Along with the Remote Electrical Tilt (RET) feature introduced around 2001 with electronical antennas, emerging antennas include the ability to reconfigure the azimuth remotely, using a remote motor control called RAZ (Remote Azimuth control), also known as beam panning. In addition, some antennas also include the ability to remotely control the horizontal beam width of the antenna, likewise
with motorized control of reflecting elements on either side of the antenna elements, or outside the radome. These are depicted in the following Figure 7.

However it is not that with these reconfigurable antennas the RF path is still passive. The remotely controlled motors are typically operated just a few times during the installed life of the antenna, usually during installation and when neighbor sites are installed or when cells are split.

**Advanced Antenna Technology**

**Base Station Antenna Evolution**

**RECONFIGURABLE BEAM ANTENNA**

- **Beam Panning**
  - Passive beam control
  - 1-way: standard RET antenna
  - 2-way: adds beam panning – horizontal beam steering
  - 3-way: adds beam fanning – horizontal beam width adjustment
  - Capacity improvements:
    - network optimization
    - load balancing
  - Dynamic coverage adjustments can be made in response to changes in traffic distribution - SON

- **Beam Fanning**

![Figure 7 – Reconfigurable beam antenna.](image-url)
1.3 INTEGRATED RADIO/ANTENNA

Figure 8 – A Three sector site configuration with Integrated Radio/Antenna units that caters for an active band with 2TX and 4 RX as well as a passive band on two antenna ports. (Courtesy of Ericsson.)

The Integrated Radio/Antenna concept is a tower-mounted unit that can replace the antenna and radio for one sector, integrating them within a single radome. There is no need for additional electronics such as Tower Mounted Amplifiers (TMAs) or a RET actuator and control. A passive antenna function for an extra band is optional.

The height and width are the same as for a passive antenna with similar characteristics. The depth is increased to house the radios’ electronics. Digital Units (DUs) provide the baseband function and support GSM, WCDMA, and LTE.

One or two DUs, depending on capacity and the standards to be supported, are needed for a three-sector site with Integrated Radio/Antenna units. The unit is especially suited for state of the art mobile broadband base stations utilizing advanced MIMO techniques. Less tower mounted equipment is required and the unit’s attractive appearance enables it to blend in well with other existing equipment. The same applies to sites with multiple access technologies on different frequency bands.

With Integrated Radio/Antennas, it is only necessary to swap existing antennas; no additional antennas are needed in order to add new 3G/4G technology on-site or at a new site. The Integrated Radio/Antenna also saves power compared to traditional RBSs.
Figure 9 shows an example of the equipment at a conventional site being integrated in a single Integrated Radio/Antenna unit. The function is the same but the implementation is different.

The Integrated Radio/Antenna unit’s active band has two radios (2) connected to a pair of cross-polarized antenna arrays (1). Remote electrical tilt (3) is included. The unit supports 2 TX branches for the down-link and 4 RX branches for the up-link.

In addition to the active antenna function (left part in Figure 9) an optional passive antenna function can be included. The passive function includes an antenna array (4) and a RET motor (5) with a modem to control it (6).

The setting of antenna tilts for the active band and the passive band are controlled independently, but within each band the same tilt is applied for both arrays and for both polarizations.
From a link budget perspective an attractive configuration on today's market is with remote radio units (RRUs) mounted close to the antenna. This will typically reduce down-link losses by 3 dB compared to a classic macro RBS configuration using a feeder system. Up-link losses are also typically 3 dB reduced when going from macro without TMAs to remote radio units. The difference with TMAs is around 0.5 dB.

An Integrated Radio/Antenna is a natural next step. The improvement compared to remote radio units is about 1 dB for both up-link and down-link due to the fact that the internal losses are reduced and active radio and antenna components are jointly optimized.

The down-link improvement can be used to improve the link budget, or to improve energy efficiency with the same link budget as for remote radio units.

The dual active columns enable four-branch RX diversity which substantially improves uplink performance. In a noise limited scenario sensitivity is improved by 3dB whereas in interference limited scenarios even higher gains are possible by means of the improved spatial selectivity. This is exemplified in the Figure 11 where the gain towards user “A” is increased while interfering signals from user “B” are suppressed.
Figure 11 – Dual column 4RX and UL Beam-Forming

Figure 12 – Three sector configuration example: Base band unit with three units

Figure 12 shows a typical configuration for WCDMA with $2 \times 2$ MIMO for Band 1. One Integrated Radio/Antenna unit is deployed in each sector and a common base band unit with a DU for WCDMA inside provides base band processing and back-haul.
1.4 ACTIVE ANTENNA SYSTEM (AAS) TECHNOLOGY

A most general approach to Digital Signal Processing controlled smart antennas, that permits not just the typical horizontal beamforming but also vertical beamforming, is made possible by these emerging active antenna arrays as detailed in Figure 13. This scheme permits amplitude and phase weights to be applied to vertically stacked antenna elements, such as the 8 co-polarized elements per column shown below (total of 32 elements). In contrast to standard passive base station antennas, where a coaxial cable distribution network divides and feeds power to each element, individual transceivers, composed of radio modems, amplifiers, and filters are located directly next to the radiating antenna elements. An integrated implementation, shown in the left side of the following figure has these transceivers, modems, amplifiers and filters integrated together as diagrammed below.

Figure 13 – The evolution of base station architectures toward more tower-top electronics, leading to the WideBand Active Antenna System (WB-AAS).
Just like the Integrated Antenna/Radio, this AAS technology has the added benefit of eliminating power losses in the RF feeder cables, much like Remote Radio Heads, but without jumper cables or connectors and their associated losses and the passive intermodulation that they can sometimes cause. With the radios integrated directly into the radome housing, and with replacement of a small number of large amplifiers with many small amplifiers, the heat is spread over the larger antenna structure as opposed to the smaller RRH or amplifier shelf, permitting larger total RF transmit powers without the use of fans or other active cooling. Additionally, the use of many lower power amplifiers, operating at cooler temperatures, can increase the reliability of the radio system, particularly when redundancy is considered. In the event of a single module failure, the overall antenna pattern is only slightly impacted and can, to a large degree, be compensated for with adjustments to the weights of the remaining active antenna elements. This reduces a radio or power amplifier failure from a critical failure mode to a maintenance issue, one that can be addressed at a convenient and scheduled time.

Clutter and wind loading on the tower are also reduced with AAS, since the separate RRH enclosure is eliminated and the worst case wind loading is set by the unchanged face of the radome. Consequently, many lease costs may be reduced.

The RF power through each RF connection to the antenna elements are reduced in proportion to the number of independent radios. Passive InterModulation Distortion tends to increase in proportion to the cube or fifth power of the signals strengths. So by distributing the power through many parallel paths the likelihood of PIM distortion is reduced, suggesting that one may be able to transmit wider
band combinations of carriers that cannot otherwise share the same transmit chains out of concern for PIM.

The principal advantage of AAS is, however, their ability to increase gain through vertical processing depicted below in Figure 15.

With AAS, one is able to electronically tilt the beam without the electromechanical RET control as shown in the upper left corner. The uplink and downlink beams can be tilted separately as shown in the upper right hand corner. This is particularly useful because the downlink beam can be tilted further down so as not to inject undue interference to adjacent cells. Note that we make a distinction between vertical sectorization wherein different CELL IDs are assigned to the inner and outer beams (highly tilted and less tilted beams) and vertical beamforming, which broadcasts the same CELLID through multiple vertical beams but with different users associated with the differently tilted beams.

![Figure 15 – Vertical beams introduce multiple means to produce gains.](image)

The architectural tradeoffs with AAS are depicted below. In this architecture the distributed transceivers, or active antenna elements, are fed digitally from a central digital processing controller and are composed primarily of three custom IC building blocks.
The critical benefit of AASs is the unique ability to electronically tilt elevation beams by having independent base band control of the phase and amplitude of the signals through each element. This supports multi-mode systems where different carriers in the same frequency band, with different air interfaces, may utilize different antenna patterns. For example, legacy CDMA carriers may provide adequate coverage, but LTE may be down-tilted differently than the legacy carriers. LTE which does not use soft handoff, and so may do better with more down tilt than CDMA for which less down tilt is preferred due to soft handoff.

Simultaneously, the LTE carrier may also be directed toward different azimuth directions than are the legacy carriers, through the standard LTE precoding schemes. The electronic tilt capability also allows for the separate beam tilting and optimization of the TX and RX paths and the vertical or vertical beamforming (without different Cell IDs) of a cell.

### 1.4.1 ACTIVE ANTENNA SYSTEM (AAS) PERFORMANCE

Preliminary simulations coupled with field measurements have led to some important lessons on the utility of AAS. Not surprisingly, much of the performance impact of introducing sectors in the elevation plane has to do with the distribution of traffic and user density as a function of elevation angle. For
example, a rural base station with few users located near the base of the antenna will have few opportunities to gain traffic from an inner sector while another base station located close to offices and population density will have the potential for gain as suggested in the figure below. Moreover, a densely urban environment with a AAS base station below the clutter will likely have high vertical angle spread, injecting interference into the alternate vertical beam.

![Figure 17](image)

**Figure 17** – Example environments with vastly different potential for AAS gains. The populated area on the left has many users close to the 140’ tower, while the rural environment on the right has few opportunities for users to populate any inner sectors.

However, in appropriate environments, recent field measurements and simulations have seen tangible gains as follows:\(^\text{12,13}\):

- **Typical Spectral efficiency gains of 30% for rooftop urban/suburban sites.**
  In the best cases three is up to 60% increase in downlink and uplink spectral efficiency.
- **Independent tilt optimization for UL/DL of the sort illustrated in Figure 15b, typically increases cell edge throughput by about 30%, based on 3GPP Case 1 simulation assumptions (in AWS band) with 500m Inter Site Distance (ISD). No gain was observed for 3GPP Case 3 simulation assumptions with 1732m ISD.**
- **In Vertical Sectorization, digital downtilts are used to form two vertical beams (sectors), each with its own physical layer cell ID. Effectively two vertical sectors are formed. Vertical Sectorization can provide a large aggregate downlink sector throughput gain (30% to 70%) compared to a single sector, but…**
  - The gain throughput is due to the gain in the inner sector alone.
  - The outer sector experiences an overall loss in throughput from intercell interference and reduced power due to sharing power with the inner beam. This means that the cell edge user throughput with vertical sectorization can actually be poorer than that without vertical sectorization.
  - For 3GPP case 3 (with 1732 meter inter-site distance ISD) the capture area of the inner sector is small and only a few users will benefit from this gain.
  - As ISD increases, the inner sector area % decreases, even as the tilt angles are optimized for the increased ISD.
  - As with any cell-splitting strategy, handoffs between two vertical sectors increase overhead.
Vertical beamforming (without different Cell IDs) is a more advanced scheme than Vertical Sectorization. In this mode, we use per user tilt with 2 or 3 preconfigured tilt angles and we use the same Cell ID for all beams (e.g., inner and outer). A single scheduler is used to handle traffic for all beams. Common channels are transmitted without beamforming for base coverage so that there is no handoff between inner and outer beams required, just like user specific beamforming, but in the vertical direction rather than the typical horizontal approach. The scheduler controls time/frequency reuse between the vertical beams for dynamic flexibility.

- The downlink gains of vertical beamforming (without different Cell IDs) for the specific scenario of 3GPP Case 1 assumptions, 2 GHz, ISD 500m, 32m BS height, 1.5m UE, no reuse of radio resources for outer/inner beams via MU-MIMO:
  - The aggregate cell throughput increase significantly by 30%.
  - The Cell Border Throughput increases significantly as well by 40%.
  - These gains cannot be assumed as generally applicable to all network sites.
  - Further spectral efficiency gain can be expected when MU-MIMO is implemented for Rel. 9+ UE.

In a sense, AAS introduces three small cells per site, one for each sector, similar to a metrocell near the base station. With vertical sectorization (without different Cell IDs) these inner beams do not contribute much to intercell interference. Unfortunately depending upon morphology and local traffic conditions, these small inner sector areas may be so small that few UEs are typically within their boundary. Consequently, much of the gains from Active Antenna Systems depend upon local conditions unique to each specific site.

1.5 High Gain Antennas for Wide Area

1.5.1 BACKGROUND

The rapid increase in mobile broadband usage has made network capacity a prime concern, with various capacity-oriented antenna solutions as described in this document offering means to improve spectrum efficiency, or throughput per unit area. Moreover, users are becoming accustomed to ubiquitous availability of mobile access to information sources, e-mail, social media, and streaming services. This translates into an expectation of being always connected, which warrants attention since it points to a need also for coverage-oriented solutions.

While capacity solutions are primarily deployed in urban scenarios with high traffic densities, pure coverage solutions are deployed to offer wireless services in areas with lower traffic densities, typically rural areas, where capacity is less of an issue. In such rural deployments, coverage is a key performance indicator and solutions that minimize the required number of base station sites are highly desirable to reduce capital expenditure and operational cost.

1.5.2 HIGH-GAIN ANTENNAS

High-gain base station antennas offer a means for improving coverage. High antenna gain is an attractive feature, giving a balanced improvement of uplink and downlink link budget. The azimuth
beamwidth is typically fixed if area coverage shall be maintained for a given sectorization, which means that the elevation dimension must be exploited. Since narrow beams are required to achieve high-gain antennas, the deployment of such antennas is suitable for environments with small elevation variations, such as flat rural areas, coastal regions, and sea coverage, i.e., environments where the users are concentrated within a narrow interval of elevation angles.

The benefit of high gain can be exploited in two primary ways. It can be used to increase the inter-site distance, thus allowing a sparser deployment of base station sites. This is particularly suitable for areas with no previous towers or other structures for antenna installation. For existing cell plans, with sites in place, the high antenna gain provides link budget improvements in terms of increased signal strength, or SNR. This improves the quality of service of existing networks, when original antennas are swapped for high-antennas, as well as new networks deployed with high-gain antennas at roll-out.

### 1.5.3 GAIN, HALF-POWER BEAMWIDTH, AND SIZE

The vast majority of antennas used in macro base station installations have elevation half-power beamwidths of around 4–15 degrees. Depending on the band of operation, this translates into approximately 1–2.5 m long antennas with antenna gains of up to 20 dBi at higher frequencies (2 GHz). For coverage solutions, the primary concern is the antenna gain since that will determine the maximum range of service. Thus, antennas with even higher gain are feasible and attractive for wide-area coverage scenarios.

Increasing the size and, hence, gain of base station antennas is a straightforward and practical way of achieving significant link budget improvements without requiring changes in base station functionality. For example, a 7 m long antenna provides 4.5 dB extra gain compared to a 2.4 m long antenna. Such an antenna used at 800 MHz has an elevation half-power beamwidth of around 2.7 degrees. Similarly, a 5 m long antenna provides 2.5 dB extra gain compared to a 2.5 m long antenna. Operating at 1900 MHz, such an antenna has 1.9 degree elevation half-power beamwidth. Both these high-gain antennas provide an efficient use of energy, by directing radiated power towards those areas and users where path loss is highest. At the same time, they maintain coverage towards areas where signal strengths are higher than what can be exploited by coding and modulation schemes, which means that no parts of the cell experience loss of performance. Logistics is simplified if the high-gain antenna can be assembled from shorter subpanels on site at time of installation.\(^{14}\)

Antennas of this type may not be allowed for urban deployment due to zoning restrictions on antenna size and EIRP (effective isotropic radiated power). For rural deployment, however, antennas are typically mounted on towers or masts, which means that the installation platform itself provides the major visual impact and also that the minimum distance from the antenna is at least the installation height. An example of the low visible impact of the 5 m 1900 MHz antenna described above is shown in Figure 18. Even with the default (gray) color scheme, the high-gain antenna has limited visual impact compared to the tower and other equipment.
1.5.4 DEPLOYMENT SCENARIOS

High-gain antennas are primarily suitable for scenarios with limited elevation angular spread. The antenna elevation beam shall be wide enough to cover the angular interval corresponding to the terrain profile of the served cell, i.e., the user distribution. Angular distributions for four different scenarios are presented Figure 19. Two different inter-site distances (ISD) are assumed, 1732 m and 5000 m, modeling relatively low-density site deployments, and the antenna height is 30 m. Normal-distributed variations in the UE vertical position is assumed with standard deviations (STD) of 5 m and 10 m, both representing flat propagation environments, and shadowing effects are ignored. The UE positions are concentrated within narrow angular intervals of about 5 and 2 degrees for inter-site distance of 1732 m and 5000 m, respectively, for both settings of standard deviation. This implies that
for flat rural scenarios with large inter-site distances, the elevation half-power beamwidth can be on the order of a few degrees or less without loss of coverage.

An example of predicted coverage from a cell planning tool is shown in Figure 20 for a standard 18 dBi sector antenna and two different high-gain antennas with 21 dBi and 23 dBi gain. These high-gain antennas have half-power vertical beamwidths of approximately 3.5 and 2.1 degrees, respectively, matching the angular distribution of the larger cell scenario in Figure 19. The coverage areas (blue) with the high-gain antennas are increased by about 40% and 60%, respectively, in this example.
1.5.5 USE CASES

Field trial data for two different use cases serve to illustrate the benefits of high-gain antenna deployment in flat regions of live networks. In both cases, dual-polarized antennas are used and the high-gain antenna results are compared with reference results for dual-polarized sector antennas with 17–18 dBi gain. All other site equipment is left unchanged, which means that the results are direct measures of the performance impact of high-gain antennas. These deployments confirm that narrow elevation beams are compatible with moderate antenna heights of about 25–30 m and that antenna alignment for proper tilt and area coverage is no issue. Although the prime objective is different for each use case, both cases provide increased SNR and range.

Cell range extension at 1900 MHz

Measured downlink received signal strength (RSS) values at 1900 MHz for an 18 dBi conventional antenna with 2 degrees tilt and a 23 dBi high-gain antenna with 0.5 degrees tilt (shown in Figure 21) are compared in Figure 21 for distances up to 22 km. Both antennas are installed about 28 m above average ground, with the standard deviation of ground elevation level being less than 5 m. The RSS values for the high-gain antenna at distances beyond 1 km are equal to or better than those of the conventional antenna. For distances of 10 km and beyond, the RSS values for the high-gain antenna is higher than those of the conventional antenna by 4–5 dB, i.e., the difference in antenna gain. This confirms that the additional 5 dB antenna gain of the high-gain antenna directly translates into increased signal strength and corresponding increase in cell range for a given minimum signal level.

SNR improvement at 900 MHz

The distribution for the difference in measured downlink RSS values at 900 MHz for a 17 dBi conventional antenna with 2 degrees tilt and a 22 dBi high-gain antenna with 0.5 degrees is plotted in

![Figure 21 – Measured downlink received signal strength versus range at 1900 MHz for antennas with 18 dBi and 23 dBi gain in area with less than 5 m standard deviation in user elevation.](image)
Figure 22, for unprocessed and fitted data. The measured data is collected within the service area defined by the conventional antenna, for distances between 3 and 8 km from the base station, by multiple drive tests over the same route for each antenna to ensure convergence. The mean difference in measured RSS is 5.5 dB with a standard deviation of 1.3 dB. This confirms that the additional 5 dB antenna gain of the high-gain antenna directly translates into increased signal strength and corresponding increase in SNR for the given service area.

Figure 22 – Distribution of difference in measured downlink received signal strength at 900 MHz for antennas with 17 dBi and 22 dBi gain, over flat area for measurement distances between 3 and 8 km from base station.

### 1.6 COMMERCIAL ANTENNA TYPES SUPPLIED – ONE VENDOR

The following table compares the distribution of antenna types recently supplied by one vendor’s North American sales.

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>%</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertically polarized (V-pol)</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Dual polarized (X-pol)</td>
<td>94</td>
<td>Dual-polarized antennas are becoming the norm.</td>
</tr>
<tr>
<td>Variable tilt</td>
<td>93</td>
<td>New antenna purchases are overwhelmingly variable tilt with RET capability.</td>
</tr>
<tr>
<td>Fixed Tilt</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>
### Antenna Type

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>%</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>RET</td>
<td>61</td>
<td>RET market share is increasing</td>
</tr>
<tr>
<td>Non-RET</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>

### Single Band Antennas

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>%</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single band</td>
<td>50</td>
<td>40% of these are quad port such as AWS &amp; PCS bands</td>
</tr>
<tr>
<td>Multiband</td>
<td>50</td>
<td>Multiband market share is increasing</td>
</tr>
</tbody>
</table>

### Elevation Beamwidth 800/900 MHz

<table>
<thead>
<tr>
<th>Beam Width (Degrees)</th>
<th>%</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>45</td>
<td>Nominal height is 1.4M</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>Nominal height is 2.0M</td>
</tr>
<tr>
<td>8</td>
<td>35</td>
<td>Nominal height is 2.6M</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Elevation Beam Width 1800/1900/2100 MHz

<table>
<thead>
<tr>
<th>Beamwidth (Degrees)</th>
<th>%</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>10</td>
<td>Nominal height is 0.7M</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>Nominal height is 1.0M</td>
</tr>
<tr>
<td>8</td>
<td>65</td>
<td>Nominal height is 1.4M</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>Nominal height is 2.0M</td>
</tr>
</tbody>
</table>

### Azimuth Beam Width

<table>
<thead>
<tr>
<th>Azimuth (Degrees)</th>
<th>%</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>15</td>
<td>Typically Rural</td>
</tr>
<tr>
<td>65</td>
<td>75</td>
<td>Urban/Suburban/Rural</td>
</tr>
<tr>
<td>33 and 45</td>
<td>10</td>
<td>Six Sector</td>
</tr>
</tbody>
</table>

The distribution of tilt settings from an operator in a mixed urban/suburban market are shown below, where each of 138 sectors have both a low frequency antenna and a high frequency band antenna. The high frequency band antennas use less tilt; with a median of 3° while the low frequency antennas use about twice the downward tilt (below the horizon). These sites had an average separation from their nearest neighbor of 1.2km and an average height of 120 feet (average angle to the nearest neighbor's base is 1.8°.)
Note that this is likely a general rule, that when co-located, the lower frequency antennas are tilted down more than the high frequency antennas because the lower frequency antenna has a larger vertical beam width and lower propagation loss. To keep intercell interference to the same level, the lower frequency antennas are typically tilted down toward the ground more than the higher frequency antennas.

Figure 23 – Tilt distribution for an operator’s deployment in a mixed urban/suburban environment showing a median of 3 degrees of downtilt for the high frequency band and 6 for the low frequency band. 20% have no tilt.
In the previous section we discussed smart antennas in which the base station’s antennas are modified in one way or another to optimize the transmission or reception of signals at the base station, where variable tilt or deployed gain is used. Multiple antenna elements may be used to shape beams in one direction or another. In the terminal, too, one may double the number of receive antennas to nearly double the received power and increase the SINR by nearly 3 dB. However, if we add antenna elements at both the base station and at the terminal then we are able to introduce an important new capability of using multiple antennas to input signals into space and multiple antennas to output the signals. This is referred to as Multiple Input and Multiple Output (MIMO), MIMO schemes are characterized by the number of antennas transmitting into the air, M, and the number of antennas receiving those same signals at the receiver(s), N; designated as “MxN.” So, for example, the downlink may use, say, 4 transmit antennas at the base station, and two receive antennas in the terminal, which is referred to as “4x2 MIMO.” The uplink might use one transmit antenna in the terminal and 4 receive antennas at the base station, for “4x1 MISO” operation. The “MxN” refers to the number of antennas in each end of the link (downlink or uplink) and not to the number of antennas at just one end of the link. As another typical example, an operator uses 2 transmit antennas in the base stations and 4 receive antennas while the terminal uses two receive antennas and one transmit, so the downlink is 2x2 MIMO and the uplink is 1x4 SIMO.

The multiple antennas at the terminal side may all be within a single user’s terminal in which case we refer to this as Single User MIMO, or “SU-MIMO.” If channel conditions are good, this single user may receive multiple streams of data, nearly multiplying the obtainable peak throughput by the number of antennas. Alternatively, Multi-User MIMO or “MU-MIMO” refers to having multiple streams destined for multiple users, multiplying the aggregate cell throughput by the number of antennas.

What constitutes an antenna? Two metal wires connected to an RF transmit or receive chain may form two antennas, but if they are wrapped around each other or otherwise too close together, their signals will be highly correlated and won’t produce distinguishable signals at the other end of the link. If the two wires are very far apart, say several km, then their coherence is challenged and it is likely that one or the other will always be received weakly at the other end of the link. A happy medium exists when two antennas are very close together but cross polarized, then their signals are both coherent and reasonably decorrelated. We see here that the nature of the channel, how much multi-path or clutter it has, as well as the physical structure of the antennas – their spacing and polarization – all affect the quality of the MIMO configuration. Different antennas perform better in certain environments and different signaling schemes (Transmission Modes or TMs) are appropriate for different antenna configurations and channels.

With the E-UTRAN (LTE) 3GPP specifications an extremely sophisticated suite of transmission modes was defined for taking advantage of a wide variety of MIMO antenna and channel situations. With LTE-Advanced, there are 9 different Transmission Modes (TMs) applicable to 1, 2, 4, or 8 base station transmit antennas and 2 or 4 terminal receive antennas. The base station’s scheduler dynamically adapts the modes to adjust the number of streams as the rank of the channel changes with time and the terminals may be requested to signal back channel state information or open loop transmit diversity can be used if special multiplexing is less effective.

This section details these schemes, and the antennas that work with them. We recognize that currently terminals are limited by power and cost to having a single transmit antenna (at least for a particular
carrier frequency) limited uplink to 1xN SIMO, consequently we focus on the downlink MIMO operation.

Figure 24 — MIMO systems.

2.1 LTE DOWNLINK MIMO BASICS

Figure 25 below shows the taxonomy of antenna configurations supported in Release-8 of the LTE standard (as described in 3GPP Technical Specification TS 36.211, 36.300). The LTE standard supports one, two, or four base station transmit antennas and two or four receive antennas in the User Equipment (UE), designated as: 1x2, 2x2, 4x2, 4x4, where the first digit is the number of antennas per sector in the transmitter and the second number is the number of antennas in the receiver. The cases where the base station transmits from a single antenna or a single dedicated beam are shown in the left of the figure. The most commonly used MIMO Transmission Mode (TM4) is in the lower right corner, “Closed loop Spatial Multiplexing,” when multiple streams can be transmitted in a rank 2 or more channel. The Transmission Modes, TM#, designation is also referred to in some literature as Antenna Cases (AC#s).
Figure 25 – Taxonomy of Smart antenna processing algorithms in Release 8 of the LTE standard. Shadows behind blocks indicate that they are capable of transmitting multiple streams.
These transmission modes are implemented through physical antennas described further in Figure 29 later in the section.

Beyond the single antenna or beamforming array cases diagrammed above, the LTE standard supports Multiple Input Multiple Output (MIMO) antenna configurations as shown on the right of Figure 25. This includes Single User (SU-MIMO) protocols using either open loop or closed loop modes as well as transmit diversity and Multi-User MIMO (MU-MIMO). In the closed loop MIMO mode, the terminals provide channel feedback to the eNodeB with Channel Quality Information through CQI, Rank Indications (RI) and Precoder Matrix Indications (PMI). These mechanisms enable channel estimation which improves the peak data rates, and is the most commonly used scheme in current deployments. However, this scheme provides the best performance only when the channel information is accurate and when there is a rich multipath environment. So closed loop MIMO is most appropriate in low mobility environments such as with fixed terminals or those used at pedestrian speeds.

In case of high vehicular speeds, Open Loop MIMO may be used, but because the channel state information is not timely, the PMI is not considered reliable and is typically not used. In TDD networks, the channel is reciprocal and thus the DL channel can be more accurately known based on the uplink transmissions from the terminal (the forward link’s multipath channel signature is the same as the reverse link’s – both paths use the same frequency block), so MIMO improves TDD networks under wider channel conditions than in FDD networks.

One may visualize spatial multiplexing MIMO operation as subtracting the strongest received stream from the total received signal so that the next strongest signal can be decoded and then the next strongest, somewhat like a multi-user detection scheme. However, to solve these simultaneous equations for multiple unknowns, the MIMO algorithms must have relatively large Signal to Interference plus Noise ratios (SINR), say 15 dB or better. With many users active in a base station’s coverage area, and multiple base stations contributing interference to adjacent cells, the SINR is often in the realm of a few dB. This is particularly true for frequency reuse 1 systems, where only users very close to the cell site experience SINRs high enough to benefit from spatial multiplexing SU-MIMO. Consequently, SU-MIMO works to serve the single user (or few users) very well, and is primarily used to increase the peak data rates rather than the median data rate in a network operating at full capacity.

Angle of Arrival (AoA) beamforming schemes form beams which work well when the base station is clearly above the clutter and when the angular spread of the arrival is small, corresponding to users that are well localized in the field of view of the sector; in rural areas, for example. To form a beam, one uses co-polarized antenna elements spaced rather closely together, typically \( \lambda/2 \), while the spatial diversity required of MIMO requires either cross-polarized antenna columns or columns that are relatively far apart. The farther apart, the more path diversity they will couple to. This is often about 10 wavelengths (1.5m or 5’ at 2 GHz). This is why most 2G and 3G tower sites have two receive antennas located at far ends of the sector’s platform as seen in the photo to the right.

LTE (4G) provides for several different variations on Multiple Input Multiple Output (MIMO) techniques, from beamforming to MIMO or single antenna schemes through selection of one of 9 Transmission Modes (TMs). These Transmission Modes (TMs) classified above in Figure 25 are detailed further in the
This table includes TM8 which is introduced in LTE Release 9 to support dual layer beamforming (Multi-User MIMO). The antenna types refer to those diagrammed in Figure 27.

<table>
<thead>
<tr>
<th>TM</th>
<th>Title</th>
<th>Antenna Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single Transmit Antenna Port 0 SIMO, rank 1</td>
<td>1 column (A)</td>
<td>For femtocells or other small eNodeBs with a single antenna. There is no diversity, beamforming nor MIMO capability. TM1 (SIMO) can also be used for macro eNodeBs in cases where &gt;1Tx MIMO is not feasible (e.g., certain antenna sharing scenarios with other 2G/3G technologies).</td>
</tr>
<tr>
<td></td>
<td>or Other antenna types with Tx only on 1 column</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Open Loop Transmit Diversity For rank 1</td>
<td>2 or 4 antennas (D, E, F, H, I)</td>
<td>The default SU-MIMO Spatial Multiplexing (SM) mode where the same information is transmitted through multiple antennas, each with different coding/frequency resources. Alamouti codes are used with 2 antennas as the Space Frequency Block Codes, SFBC. This is a common fallback mode with dynamic adaptation from other MIMO and beamforming modes. This uses Space Frequency Block Coding (SFBC) for 2TX and SFBC + Frequency Shift Time Diversity (FSTD) STX for 4TX. It has no dynamic adaptation.</td>
</tr>
<tr>
<td>3</td>
<td>Open Loop Spatial Multiplexing SU-MIMO with Cyclic Delay Diversity, CDD Multi-Stream For ranks 2 to 4</td>
<td>2 or 4 antennas (B, D, E, F, H, I)</td>
<td>As an open loop mode, this requires no PMI or other channel state information from the UE, and is used for channels that are rapidly changing such as with high velocity UEs. Precoding uses the following table as defined in 3GPP TS 36-211 Table 6.3.4.2.3-1:</td>
</tr>
</tbody>
</table>

Table 2 – eNodeB Transmission Modes in Release 9 of LTE
<table>
<thead>
<tr>
<th>Code Book</th>
<th>1 Layer</th>
<th>2 Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \ 1 \end{pmatrix} )</td>
<td>( \frac{1}{\sqrt{2}} \begin{pmatrix} 1 &amp; 0 \ 0 &amp; 1 \end{pmatrix} )</td>
</tr>
<tr>
<td>1</td>
<td>( \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \ -1 \end{pmatrix} )</td>
<td>( \frac{1}{\sqrt{2}} \begin{pmatrix} 1 &amp; 1 \ 1 &amp; -1 \end{pmatrix} )</td>
</tr>
<tr>
<td>2</td>
<td>( \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \ i \end{pmatrix} )</td>
<td>( \frac{1}{\sqrt{2}} \begin{pmatrix} 1 &amp; 0 \ i &amp; -i \end{pmatrix} )</td>
</tr>
<tr>
<td>3</td>
<td>( \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \ -i \end{pmatrix} )</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>

The 2 antenna patterns arising from these codebook entries are shown in Figure 26. The Cyclic Delay Diversity, CDD, creates additional time diversity.

| 4 | Closed Loop  | 2 or 4 antennas (B, D, E, F, H, I) | This has been the primary configuration for the majority of initial Release 8/9 deployments, operating while the channel has rank 2 to 4. It multiplexes up to four layers onto up to 4 antennas.

To allow the UE to estimate the channels needed to decode multiple streams, the eNodeB transmits Reference Signals (RS) on prescribed Resource Elements. The UE replies with the PreCoding Matrix Indicator (PMI) indicating which precoding is preferred from the codebook given above for TM3.

This is used for Single User, SU-MIMO. |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Closed-Loop Multi-User MIMO</td>
<td>2 or 4 antennas (B, C, E, F, H)</td>
<td>Similar to TM4 but for the multi-user case.</td>
</tr>
</tbody>
</table>

| 6 | Closed Loop Rank 1 Precoding | 2 or 4 antennas (D, E, F, G, H, I) | For a single layer (rank 1) channel, this mode uses PMI feedback from the UE to select the preferred (one layer) codebook entry from the codebook given in TM3 above.

Precoding the signal at baseband for the different antennas.
<table>
<thead>
<tr>
<th>Multiplexing</th>
</tr>
</thead>
<tbody>
<tr>
<td>results in the beamforming shown below in Figure 26.</td>
</tr>
</tbody>
</table>

This precoding beamforming selected by UE PMI feedback is not cognizant of multi-user intercell interference and is somewhat distinct from the classical beamforming based upon Angle of Arrival or similar approaches used in TM7 and TM8.

<table>
<thead>
<tr>
<th>7</th>
<th>Single Layer Beamforming (angle of arrival) for port 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual Antenna port 5 made from (B, C, E, G)</td>
<td></td>
</tr>
</tbody>
</table>

In this mode, both the data and the Reference Signals (RS) are transmitted with the same UE-specific antenna weights which form a virtual antenna pattern (Antenna port 5) so that the UE does not distinguish the actual physical antennas as in the classical beamforming approach.

The specific method of calibration and determining weights is left to implementations such as Angle of Arrival (AoA), MUSIC\textsuperscript{15} or ESPRIT\textsuperscript{16}.

TM7 is mainly used with TD-LTE where the channel state is well characterized and it is not appropriate for FDD-LTE.

<table>
<thead>
<tr>
<th>8</th>
<th>Dual layer beamforming based upon angle of arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual antenna ports 7 and 8 Made from (C, E, G)</td>
<td></td>
</tr>
</tbody>
</table>

Introduced in Release 9, TM8 does classical beamforming with UE specific RSs, like TM7 but for dual layers. This permits the eNodeB to weight two separate layers at the antennas so that beamforming can be combined with spatial multiplexing for one or more UEs.

The two layers can be targeted to one or two UEs.

TM8 is mainly used with TD-LTE. TM8 can also be used in vertical beamforming enabled by an Active Antenna System.

<table>
<thead>
<tr>
<th>9</th>
<th>8 Layer MU-MIMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ports 7 to 14</td>
<td></td>
</tr>
</tbody>
</table>

Introduced in Release 10, as part of LTE-Advanced, TM9 implements 2, 4 or 8 virtual ports. It is the only TM suitable for 8 ports, and most suitable for MU-MIMO with dynamic switching from SU-MIMO. It is applicable to either TDD and FDD systems.

For transmit modes 3 through 6, precoding is used to phase the signals on multiple antennas to concentrate the antenna pattern toward various horizontal directions when transmitting to a UE on the downlink. The UE sends a feedback message that recommends the precoder matrix that will optimize the quality of the link between the base station and the UE. For the case of two antenna columns, the precoding coefficients given in table entry TM3 yield the horizontal antenna gain patterns shown below in Figure 26. The two antenna columns are assumed to be separated by $\lambda/2$, with antenna type “B” - from Figure 27, and perfect antenna array calibration is assumed. Here we can see that codebook entry 1 would be appropriate for transmitting a UE located to the left or right of the antenna’s bore sight. Note that codebook entry 1 provides less interference to UEs in other cells that are located in the antenna’s bore sight. Codebook entry 2 would be best for a UE located to the right of the bore sight. Notice that
codebook entry 2 will reduce interference into adjacent cells to the left of bore sight, helping to improve the typical SINR for the network’s UEs.

Figure 26 – Antenna patterns resulting from the two antenna codebook entries of TM3, TM4 and TM6. The views are horizontal cuts as seen from above with the two antennas spaced by half a wavelength and represented by the red dots. The element factor is taken from 3GPP TR 25.996. This assumes a spacing of λ/2 and perfect calibration.
A 4-antenna version of the above figure includes 16 different antenna patterns. They would be generated by a linear array of 4 antenna columns such as in antenna style C in Figure 27. However, this antenna is not commonly used today because it is twice as wide as antenna type E which provides cross polarization diversity advantage.

### 2.2 ANTENNAS FOR MIMO

MIMO systems place the same requirements on the RF link as do the receive diversity systems that are in place for current cellular networks, that is, there must be decorrelation between the channels received at the antenna. This decorrelation is provided by space diversity when achieved by the separation of the antennas, or by the use of polarization diversity when implemented by the use of orthogonal antenna elements.

Early cellular systems employed spatial diversity and typically used two vertically polarized antennas separated by a distance of 10 wavelengths, or greater, at the frequency of operation. Most cellular providers have switched to polarization diversity, utilizing cross polarized antennas, which have been shown to provide equivalent if not better diversity gain than it does for spatial diversity. Dual polarized antennas have the added benefit of integrating two antenna arrays into one radome housing while maintaining the same size.

Most antenna properties, and their associated specifications, influence the illuminated coverage of the cell site topography and the link budget between the base station and handset. However, for dual-pol antennas, cross-polar discrimination and port-to-port isolations can affect the diversity or MIMO performance of the system by introducing correlation between the channels. Studies have shown that the standard specifications that meet the requirements for effective receive diversity performance also provide adequate decorrelation for effective MIMO system performance.

In summary, a standard dual polarized antenna (e.g. antenna D in Figure 27) works well for 2x2 MIMO, as do two spatially separated dual-pol antenna for 4x2 or 4x4 MIMO. A quad antenna, which packages two dual polarized arrays into one radome (e.g. antenna type E in figure 27), provides effective 4x2, or 4x4 MIMO performance in a compact width radome. With the two columns of cross-pol elements, the antenna can transmit on two cross polarized elements in the two columns, and receive on all 4 branches, or if 4 transmit RF chains are used, then 4x2 MIMO can be used in the downlink. Spatial separation of 1λ between dual-polarized arrays is the norm for quad antennas. Studies presented in this paper indicated that quad antennas that have a spatial separation of less than 1λ can provide throughput gains for closed-loop, spatial multiplexing, pre-coded beamforming (LTE transmission mode AC4) albeit at the possible expense of degraded diversity performance and some compromise in antenna performance.

Physically, these antennas are categorized below in Figure 27 where the short lines correspond to individual antenna elements, typically arranged in columns. Such columns are able to define the vertical beam width required to properly illuminate a cell sector and which is a characteristic of base station antennas. Typically the antenna elements in each column are interconnected and share a common RF connector shown below the columns. These correspond to the individual RF cables that connect the radios and their amplifiers. The configurations shown are restricted to no more than 4 cables per sector, corresponding to the 4x4 limit in the Release 8/9 standard.
<table>
<thead>
<tr>
<th>Trans. Mode</th>
<th>Antenna Config.</th>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM1</td>
<td>1V</td>
<td>(A)</td>
<td>1 Column with vertical polarization (V-Pol)</td>
</tr>
<tr>
<td>TM5</td>
<td>ULA – 2V</td>
<td>(B)</td>
<td>2 Closely spaced V-pol columns</td>
</tr>
<tr>
<td>TM7 (TDD)</td>
<td>ULA-4V</td>
<td>(C)</td>
<td>4 V-pol columns</td>
</tr>
<tr>
<td>TM2-4, TM6</td>
<td>DIV 1X</td>
<td>(D)</td>
<td>1 Column with dual-slant-45 polarization (X-pol) for 2 branch MIMO</td>
</tr>
<tr>
<td>TM2-6</td>
<td>CLA-2X</td>
<td>(E)</td>
<td>2 Closely spaced X-pol columns (Quad Port) 4 branch MIMO or 2 antenna beamforming</td>
</tr>
<tr>
<td>TM2-6</td>
<td>CLA-3X</td>
<td>(F)</td>
<td>1 X-pol center column between two closely spaced x-pol columns. The outer columns have only one polarization active, the other two are shown in dashed lines suitable for use with another frequency band or for “padding.”</td>
</tr>
<tr>
<td>TM2-6</td>
<td>CLA-4X (aka BM-4X)</td>
<td>(G)</td>
<td>4 X-pol columns with dual Butler Matrix TM9 can use up to 8 ports without a Butler Matrix for 4 antenna beamforming The Butler matrix in antenna G is used to distribute phase and amplitude weighted contributions of the 4 RF connectors to the 8 columns to form 4 separate beams (two for each polarization, each half as narrow a beam width as antenna E).</td>
</tr>
<tr>
<td>TM2-6</td>
<td>DIV-2X</td>
<td>(H)</td>
<td>2 Widely spaced X-Polarized columns</td>
</tr>
<tr>
<td>TM2-4, TM6</td>
<td>TX-DIV</td>
<td>(I)</td>
<td>2 Widely spaced Vertically polarized columns</td>
</tr>
</tbody>
</table>

Figure 27 — Antenna configurations with the constraint of no more than 4 antenna cables per sector for a total of 12 cables for a 3 sector system. (ULA=Uniform Linear Array, DIV=Diversity, CLA=Clustered Linear Array) The color code for the RF Coaxial connectors is the same as for the elements, except for the Butler Matrix case. These illustrative diagrams represent a single band. Additional frequency bands may be overlaid within the radomes containing these antenna elements.

No one antenna configuration is applicable to all environments, for example, in rural areas where the eNodeB antennas are located above the clutter, antennas that can form beams such as C and G are best. In urban macrocellular environments where angle spread is large, cross-polarized antennas E, G, or H give best gains from polarization diversity. In urban microcellular base stations that are embedded in the clutter and the angle of arrival spread is large, then the antenna (H) is expected to be good at providing the greatest path diversity Comparable Downlink Spectral Efficiency.
Previous measurements, simulations, and estimations of the relative spectral efficiency of various air interface technologies and antenna schemes are summarized in Figure 28 below.\textsuperscript{20}

\begin{center}
\includegraphics[width=\textwidth]{figure28.png}
\end{center}

\textbf{Figure 28 – Summary of downlink spectral efficiencies for various air interfaces and antenna schemes.}\textsuperscript{‡}

This figure clearly shows the relative performance of HSPA vis-à-vis LTE where HSPA with type 3 terminals implementing Mobile Receive Diversity (MRxD) effectively double HSPA’s spectral efficiency from 0.5 bps/Hz/sector to 0.9 bps/Hz/sector while LTE with 2X2 MIMO provides 1.5 bps/Hz/sector. The 2x2 MIMO gives HSPA a 20% increase over MRxD, but 64 QAM capable terminals and Successive Interference Cancellation (SIC) can raise HSPA efficiency to 1.3 bps/Hz/sector. Further improvements can be obtained in Release 9 HSPA with dual-carrier operation with MIMO. Note that the upgrade to 64QAM can be implemented with a software upgrade in most base stations while MIMO requires a change in antennas, though the contribution of 64QAM modulation is slight due to the rarity with which it can be expected to be available in typical cellular network operation.

\textsuperscript{‡} These values are from a joint analysis by 4G Americas’ members based upon 5+5 MHz for UMTS-HSPA/LTE and CDMA2000, and 10 MHz DL/UL=29:18 TDD for WiMAX, and assuming a mix of mobile and stationary users.
It is important to note that the gain of 2x2 MIMO in the case of HSPA+ assumes that all terminals have two receive antennas. In a deployment where there are legacy terminals without 2 receivers and MIMO capability, the multi-stream transmissions from the base stations transmitting SU-MIMO signals will contribute multi-path interference to older terminals and actually degrade the overall throughput in proportion to the percentage of terminals that do not support MIMO.

The LTE values show 2x2 MIMO with 1.5 bps/Hz/sector moving to 1.73 with SIC or general interference cancellation and 4x2 MIMO. This 4x2 operation uses a simplified switched-beam approach standardized in Release 8. Downloadable codebooks, which are being discussed in 3GPP for future releases of the standard, have potential for future improvements beyond the 2.4 bps/Hz/sector with 4x4 MIMO, although the implementation of these types of adaptive antenna and beamforming algorithms are based on proprietary algorithms so the gains are implementation dependent and may evolve with field experience.

### 2.2.1 TYPICAL 4 BRANCH CLUSTERED LINEAR ARRAY (CLA-2X) ANTENNA

Figure 29 illustrates a typical dual polarized array with 4 columns of cross-dipole radiators, a calibration circuit, and 9 connectors. Generally, 1.5 VSWR is required on all antenna and calibration ports. Isolation between co-polarized and cross-polarized antenna ports is desired to be greater than 25 dB and 30 dB respectively.

A beamforming antenna can be used in either broadcast mode or beamforming mode. In broadcast mode, a typical 65° azimuth beam width is required for a tri-sector system with approximately 17 dBi gain. In beamforming mode, a 4-column array can provide an additional 6 dB antenna gain at boresite reducing to about 3 dB additional gain at maximum scan of ±60°. For MIMO applications, cross-polarization rejection between the orthogonal +45/-45 polarized ports of 20 dB at boresite and 10 dB over sector (±60°) is typically required.

A broadband multicolumn antenna with Remote Electrical Tilt (RET) would need to have similar elevation pattern performance of a fixed tilt antenna over a downtilt range of typically 0°-10°. To reduce adjacent cell interference, typically 16 dB upper sidelobe suppression is required.

For beamforming accuracy, a calibration circuit is required to reduce effects of transceiver variations between paths. The passive calibration circuit typically requires amplitude balance between paths of < 0.7 dB and phase balance of < 5°.
2.2.2 MULTI-BEAM ANTENNAS

Multi-beam antennas are starting to be used in cellular networks where it is desired to increase capacity of existing cells. A single sector antenna can be replaced by two or more cell sectors. For this it is convenient to replace the single sector antenna with an antenna providing two or more beams in the horizontal plane.

Another application is where an area with extremely high traffic density must be served from a single point. This frequently arises in the context of stadiums or open-air venues such as music concerts or sports events. Here, different sectors of the crowd are covered by separate narrow beams. Because music events and the like are often one-time or annual events, there is growing interest in high capacity COW (cell-on-wheels) systems with multi-beam antennas providing horizontally sectorized multiple cell coverage that can be moved in to cover the particular event. A typical panel antenna for covering such a crowd is a cross polarized 9 column antenna (2x9 ports) to produce 9 sectors with dual branch receive as shown below in Figure 30. The left figure is for an array of 10x6 elements driven from a Butler matrix with...
5 inputs forming the five beams shown and the right figure is from an array of 20x6 elements used to form 9 cross polarized beams.

![Multi-beam transmit patterns](image)

Figure 30 – Multi-beam transmit patterns. The left figure corresponding to an antenna array with a center beam gain of 20.5 dBi; the right figure has a center beam gain of 23 dBi.

The technology seems to have application for capacity enhancement in many situations. Another example tilts the two polarizations separately tilted to produce two rows of 9 beams as shown in Figure 31. This product is touted for covering tiers of bleachers in sports stadiums.

![Multi-Beam Antenna array pattern for 2 rows of 9 beams](image)

Figure 31 – Multi-Beam Antenna array pattern for 2 rows of 9 beams.

Two-beam antennas have been implemented as RET antennas with the networks implemented in each row of the array. This is also possible with multi-beam antennas; however the complexity rapidly grows with the number of beams.

The basic antenna consists of an array of dual-polarization columns fed from two butler matrices so as to obtain a number of beams pointing at different azimuth angles.

A butler matrix is a microwave network with \( n \) input ports and \( n \) output ports allowing the forming of up to \( n \) beams when connected to the \( n \) port antenna. The input ports are all matched and isolated from each other as are the output ports. The network has the special characteristic that if a signal is applied to input
port $i$ ($i=1,\ldots,n$) then the output $j$ ($j=1,\ldots,n$) has phase $360\cdot\frac{(j-1)(i-1)}{n}$ degrees, which means that feeding element $i$ radiates a beam at azimuth of $\sin^{-1}\left[\frac{\lambda}{s}\cdot\frac{i-1}{n}\right]$ where $s$ is the spacing of the columns.

### 2.2.3 AN ANALYSIS OF ANTENNA CONFIGURATIONS FOR 4X2 AND 4X4 MIMO

An attractive base station antenna solution for LTE supporting up to four layers in the downlink is to use two horizontally separated dual-polarized antennas such as shown to the right. This enables a compact antenna design that can utilize both the spatial and polarization dimensions. The amount of separation between the two antennas will have different impacts on the potential gains of beamforming, diversity, and spatial multiplexing. Realizing these gains puts conflicting demands on the antenna separation and different choices of antenna separation will result in different system performance profiles. The antenna size is also an important parameter from a site installation point of view. It influences various aspects, e.g., visual footprint, wind load, and site rental cost.

Results from a study on the impact of antenna separation on LTE system performance are presented. By means of system simulations, evaluations are performed to aid the understanding of the antenna separation trade-off. In addition, empirical support to the simulation results is provided by means of comparison to results from a measurement campaign.

The simulations were performed with a detailed dynamic system simulator that includes models of adaptive coding and modulation, UE mobility, and delays in channel quality reports. It also contains an implementation of the 3GPP spatial channel model (SCM) and the mutual information based link-to-system interface described in "A Fading-Insensitive Performance Metric for a Unified Link Quality Model."

A simulation scenario similar to the defined 3GPP case was evaluated for different configurations with dual-polarized antennas at the BS using the closed-loop spatial multiplexing transmission mode (transmission mode 4). 3GPP case 1 refers to a macro-cell reference system deployment type with the 3GPP SCM used for channel modeling. The network consisted of 19 sites separated 500 m with 3 cells per site and an average traffic load of 4 UEs per cell. Each antenna port of the BS antenna was modeled according to the BS antenna model regardless of antenna separation. The notation $n_{tx} \times n_{rx}$ will be used for an antenna configuration with $n_{tx}$ transmit and $n_{rx}$ receive antenna elements. Downlink (DL), 4x4, 4x2, and 2x2 configurations comprising one or two dual-polarized antennas at the UE and BS are investigated. For uplink (UL), 1x4 and 1x2 configurations comprising one vertically polarized antenna at the UE and one or two dual-polarized antennas at the BS (The E-UTRA standard for LTE assumes the use of at least two antennas in the UE, at least as a baseline.) Wideband PMI and frequency selective CQI was assumed in the simulations.

Next we consider the performance impact of changing the separation of two columns of base station antennas, such as (H) in the figure above.
The left plot Figure 32 shows normalized downlink (DL) bit rate for the 4x4 antenna configuration as a function of the separation given in wavelengths, $\lambda$, between the two BS antennas. Three different metrics are shown; cell throughput, cell edge bit rate, and peak bit-rate. These metrics are defined by the average cell throughput, and the 5- and 95-percentile of the CDF of the active radio link bit rate (ARLBR), respectively. The ARLBR is the user bit rate averaged over the time a user has been assigned resources. The bit rates have been normalized in such a way that it is one at $1\lambda$ separation between the dual-polarized BS antennas for each percentile curve. The middle plot shows results from the 4x4 antenna configuration of the probability of a certain transmission rank as a function of the two dual-polarized antennas separation. The results in the left plot show that the cell throughput and cell edge bit rate decrease as the Base Station’s antenna separation increases, while it is essentially constant for peak rate. There is a benefit of a small antenna separation in this scenario since it is interference limited; hence, beamforming gains are more important than spatial multiplexing gains. The rank statistics in the middle plot show that rank 1 and 2 are most probable for small antenna separation. As the separation increases, the probability of rank 3 transmission increases. Almost no rank 4 transmissions occur, since the signal-to-interference-and-noise ratio (SINR) is too low in this scenario. Corresponding UL results for a 1x4 configuration are shown in the right plot in Figure 34. The results show that in this case the bit rate increases (except for the cell edge bit rate at 10$\lambda$) as the separation between the dual-polarized antennas increases. This is because the diversity gain increases with increased co-polarized antenna separation.
Figure 33 shows a summary of the performance with different configurations for DL and UL in networks with high load, as well as in networks with low load. The bit rates have been normalized so that it is one for corresponding 2x2 and 1x2 results for DL and UL, respectively. Two different antenna separations are compared: 1λ and 10λ, representing small and large separation, respectively. In the low load network scenarios shown, there are on average 0.1 UEs/cell. The results show that for DL, a small antenna separation gives highest performance for all cases except for peak throughput at low load. For UL, large antenna separation gives highest performance in all cases. However, most of the UL gain in going from two to four antennas is achieved also with 1λ separation.

In order to allow comparison to measurement results, Figure 34 shows throughput CDFs for a full system simulation with an average of 4 UEs/cell, simulation of a single UE single cell (SUSC) scenario, and for the SUSC field trial results, respectively. These results are for 4x4 configurations and each plot shows CDFs for two antenna separations; 0.7λ and 25λ. The results are normalized to the median of the full
system simulation CDF for the antenna separation of 0.7λ. The measurements were performed using a single UE in a single cell scenario and only downlink performance was addressed. In order to simulate a SUSC scenario, all intercell interference was turned off in the simulator. In these simulations somewhat different parameter settings were used to better reflect the trial scenario, e.g., getting a similar signal-to-noise ratio (SNR) range in simulations and trials. The purpose of the comparison is not to reach an accurate agreement in terms of absolute performance numbers, but rather to illustrate that the relative performance between different configurations show similar behavior.

Similar to previous results, the full system simulation shows that a small antenna separation gives the highest throughput. In the SUSC simulation and the field trial, the configuration with large antenna separation gives higher throughput for UE positions with good channel quality. In these cases, the SNR is sufficiently high to benefit from the additional spatial multiplexing gains offered by the uncorrelated antennas.

### 2.3 Antenna Array Calibration

Antenna arrays that are used to perform the various forms of beamforming or antenna precoding described in this white paper generally require some form of calibration to control the relative amplitude and phase values on the transceivers that drive the antenna array. (Note that we are distinguishing antenna precoding from beamforming by using the term precoding to refer specifically to the TM modes in LTE, for example that perform UE-specific beamforming at baseband based on PMI-feedback (as in TM4 or TM9) or Sounding Reference Signals (SRS) (as in TM7 or TM8). In general, errors in amplitude and/or phase response in the transceivers behind the array can degrade the performance of the beamforming or precoding, and the level of degradation depends on the particulars of the beamforming or precoding strategy and the associated calibration strategy being used.

This section describes the antenna array calibration requirements for three common situations. The first subsection describes the calibration requirements for a beamforming antenna array where the important issues of concern are the key characteristics of the antenna array radiation pattern, most notably the beamforming gain and sidelobe behavior of the overall array. The second and third subsections describe the calibration requirements for antenna arrays involved in adaptive per-user precoding where the precoding weights are applied at baseband and the key metrics of concern are the quality of the overall link between the transmit array at the base station and the UE (e.g., TM4, TM7, TM8, or TM9 in LTE). The second section deals with how calibration errors can actually degrade the performance of codebook-feedback based precoding for Single-User MIMO (e.g., TM4, TM9) as well as for Multi-User MIMO (e.g., TM9). The third section deals with how calibration errors in TDD can degrade the performance of SRS-based precoding (e.g., TM7, TM8 in LTE) that leverages the UL/DL reciprocity of a TDD system.

#### 2.3.1 Calibration Requirements for Beamforming

Beamforming quality depends on the relative accuracy of the amplitude and phase values of each transceiver. As with all multi-column beamforming antenna systems, there is some degree of error due to undesirable variations between each transmit and receive path. With beamforming, some type of calibration method must be implemented to minimize the amplitude and phase errors between transceivers and antenna columns. Figure 35 below shows the comparison of a beam synthesized without any amplitude or phase errors as compared to a beam synthesized with random amplitude and
phase errors. For this particular example, random amplitude errors of ±0.5dB and random phase errors of ±20° were applied simultaneous to each transceiver of an 8-column beamforming antenna array.

As can be seen in the patterns in Figure 35, phase and amplitude errors can result in significant beamforming degradation. The degraded patterns may result in undesirably high side-lobe levels, squinting of the main beam, and degradation in gain, as well as losing the ability to accurately position nulls. Typical beamforming systems deployed today require that amplitude variations be limited to +/- 0.5dB, while phase variations are limited to no more than +/- 5 degrees.

Calibration networks for beamforming antennas can be implemented by integrating directional couplers on individual antenna paths. The coupled outputs are then combined and connect to a dedicated calibration transceiver. A typical calibration network block diagram for a 4-column beamforming antenna array is shown below in Figure 36. By selectively powering up individual transceivers, the amplitude and phase characterization of each antenna path can be achieved.
The calibration network shown in Figure 36 allows for periodic automated calibrations. Typically, these calibrations would take place at periods of low traffic usage, but essentially can be performed at any time. It is important to note that the power divider network and directional couplers must be carefully designed and calibrated such that they do not contribute additional amplitude and phase errors. These types of networks require careful s-parameter characterization at the factory level to ensure that adequate performance levels are achieved.

For beamforming antennas with additional columns, there will be an obvious increase in cost and complexity of the calibration networks. Some lower cost calibration networks have eliminated the need for couplers, combiners and dedicated calibration transceivers. These lower cost calibration networks exploit the strong mutual coupling of the adjacent antenna columns to establish phase relationships between columns. A separate calibration transceiver is not required in TDD systems, but instead, the main transceivers are used for calibration activity. While these types of calibration networks are lower cost and lower complexity, they do require more complex algorithms for extracting the calibration data.

It is important to note that the amplitude and phase errors are proportional to the operating frequency. Beamforming antenna systems operating at 2.5 GHz and 3.5 GHz will observe phase variation significantly higher than for a system operating at 850MHz. These increased errors are due to the natural tolerance variations of the transmission line paths at higher frequencies.
2.3.2 EFFECT OF CALIBRATION ERRORS IN DL SU-MIMO AND DL-MU-MIMO WITH CODEBOOK-FEEDBACK-BASED PRECODING

As mentioned in Section 2, LTE Releases 8 through 10 support two main forms of closed-loop MIMO on the downlink: Single User MIMO (SU-MIMO) and multi-user MIMO (MU-MIMO). The term “closed-loop” refers to how the DL MIMO methods employ some level of knowledge of the downlink channel to perform beamforming of one or more data streams to either one user at a time (SU-MIMO) or to two or more users at a time (MU-MIMO). Typically, Precoder Matrix Indication (PMI) is computed by the UE and feedback to the eNB, and the eNB can either apply the transmit beamforming weights indicated by the PMI directly (e.g., in the case of SU-MIMO) or the eNB can compute vendor-specific transmit beamforming weights based on the PMI feedback (e.g., in the case of MU-MIMO). In PMI feedback, a codebook of possible transmit beamforming matrices is maintained at both the eNB and the UE, and the UE selects and feeds back the PMI that corresponds to the preferred transmit beamforming matrix that will optimize the downlink performance for the UE.

During downlink data transmission, the beamforming or precoding weights for DL-SU-MIMO and DL-MU-MIMO are generally applied in the frequency domain at baseband prior to up-mixing to RF. As a result, for optimal performance the precoding weights must be optimized for a channel that includes the baseband-to-RF conversion process at the transmit array in addition to the RF multipath channel between the physical antennas and the UE(s). When DL-SU-MIMO and MU-MIMO is performed based on PMI feedback, the UE computes the preferred PMI based on an estimate of the downlink channel that includes the baseband-to-RF upmixing and the RF multipath channel. As a result, the PMI is optimized for the actual channel over which the DL data will be transmitted. However, the codebooks in LTE were designed assuming the transmit array was a “calibrated” array, where the term “calibrated” is used here to mean a transmit array in which the transmit hardware responses do not modify the spatial nature of the overall channel response between the baseband at the transmit array and the receive antennas. In a calibrated array, the transmit branches all effectively have identical frequency responses (to within a common complex constant) from baseband to the physical antenna ports at RF. In an uncalibrated array, the frequency responses on the transmit branches may be different, which will cause the statistical characteristics of the overall downlink channel to deviate from those seen with a calibrated array. As a result, with an uncalibrated transmit array, the performance of the codebook feedback-based DL transmissions will be affected since the codebooks in Rel-8 and Rel-10 were designed to span the RF multipath channels seen by calibrated arrays.

In a realistic implementation of a transmit array at an eNB, there are a variety of factors that will cause a transmit array to be uncalibrated. Two of these factors studied in 3GPP (see [28] and [29]) are wideband phase errors and time alignment errors. Time alignment errors (TAE) are timing differences between the transmit branches and cause the signal transmitted on each branch to be transmitted with a different delay. The different time delays cause each transmit branch to have a different frequency-selective phase ramp across the transmitted signal bandwidth, where the rate of change of the phase across the bandwidth is proportional to the relative time delay of the branch. As a result, these different phase ramps cause the overall spatial channel response between the baseband of the transmit array and the UE to vary more rapidly across the frequency bandwidth than it otherwise would. In DL SU- and MU-MIMO, a single set of precoding transmit weights are typically applied across a data allocation and are therefore unable to track any channel response variations that occur within the allocation. Therefore, any increase in the channel response variations across the allocation will degrade the performance of SU and MU MIMO in wideband allocations due to the inability to track those variations. Narrowband allocations tend to suffer less degradation than wideband allocations due to less channel response variation across a
smaller allocation. MU-MIMO transmission tends to suffer more degradation than SU-MIMO due to the need to accurately point nulls to minimize the cross-talk received at multiple UEs. Even though the degradations with time alignment errors are more severe in wideband allocations than in narrowband allocations, narrowband precoding in narrowband data allocations does not appear to fully mitigate the time alignment problem in all cases (see [30]).

Another factor studied in 3GPP is wideband phase errors on the transmit branches. Even if all the branches of the transmit array are perfectly time aligned, each transmit branch may still have a different gain and phase response due to a variety of implementation-specific factors. In 3GPP, a simplistic model for wideband phase errors was used where the frequency response on each transmit branch was modeled to be constant in amplitude across frequency with a random phase that is fixed in time and non-selective frequency. Unfortunately, a realistic implementation may have variations in the overall frequency response of the different transmit branches that are more complicated to model than a simple random wideband phase error term across the branches.

In 3GPP, a simulation study was performed to assess the magnitude of the degradations that occur when time misalignment and wideband phase errors cause the transmit branches to be un-calibrated. The presence of these calibration errors result in overall channel responses that the LTE codebooks may not span well (this effect is called the codebook quantization error problem), which was shown to be a bigger problem for MU-MIMO than SU-MIMO given the accuracy required in MU-MIMO to point nulls for effective cross-talk mitigation. It was shown in [31] that the performance of SU-MIMO was relatively insensitive to time alignment and wideband phase errors. However, DL MU-MIMO performance was often severely degraded by such errors. Wideband phase errors generally cause only minor degradations in MU-MIMO transmission with the exception of uniform linear arrays operating in line-of-sight channels, in which case the degradations are severe. With narrowband allocations, time misalignment errors tend to cause only minor degradations with the exception of a uniform linear array operating in line of sight channels, where the degradations are severe. With wideband allocations, time misalignment often causes extreme levels of performance loss from the performance with perfectly calibrated transmit arrays.

2.3.3 CALIBRATION REQUIREMENTS FOR RECIPROCITY-BASED PRECODING IN TDD SYSTEMS

In static Time-Division Duplex (TDD) channels, the propagation environment is known to be reciprocal in uplink and downlink due to both uplink and downlink occupying the same bandwidth on the same carrier frequency. In TDD systems (e.g., LTE TM7 and TM8), a common technique for transmit precoding is to measure the uplink channel responses to a particular subscriber (e.g., by leveraging the Sounding Reference Signals transmitted by the UE) and use the measured uplink channel responses as an estimate for the downlink channel. The transmit weights used by the transmit beamformer are then calculated based on the estimated downlink channel response. Although the uplink and downlink RF channel responses are reciprocal (assuming no time variations in the channel between uplink and downlink) the transmit and receive hardware at the base station are generally not reciprocal. The uplink channel measured by the base station includes the base station receive hardware and the subscriber transmit hardware; while the downlink channel through which the beamforming is performed includes the base station transmit hardware and the subscriber receive hardware. Unless a calibration is performed, the transmit and receive hardware across an antenna array are generally not identical in their gain and phase responses, and the differences must be accounted for by any transmit array algorithm that leverages UL/DL reciprocity. This accounting for the transmit and receive hardware is the essence of the
calibration problem for reciprocity-based antenna arrays. Typically, a base station that exploits uplink/downlink reciprocity in TDD will have a calibration mechanism for insuring that the spatial channel measured on the baseband of the uplink is equivalent to the downlink spatial channel over which the transmit beamforming will be performed. References [32], [33], and [34] provide an overview of the reciprocity calibration problem and propose a methodology for reciprocity calibration. Other techniques for reciprocity calibration are possible, and generally the calibration mechanism is a vendor-specific function. Typically a reciprocity calibration mechanism will involve first measuring the forward and reverse path gains of the transceiver hardware and compensating for the forward and reverse differences when computing the downlink transmit beamforming weights. The calibration mechanism is typically not something that has to be performed very often because the variations in the hardware responses are generally caused by changes in temperature and other slowly varying factors.

3 RECONFIGURABLE BEAM ANTENNAS

Here we consider antennas with electromechanically controlled beam patterns. These are distinct from the fully electronically adaptive antenna systems that can apply a different tilt or beam pattern per user, as described in the earlier sections on AAS and electronic beamforming antenna schemes.

3.1 HOW RECONFIGURABLE BEAM ANTENNAS WORK

Reconfigurable beam antennas extend the range of remote beam changes from a single dimension for elevation beam steering (Remote Electrical Tilt, RET) to multiple dimensions. These antennas include the possibility to change the boresight or azimuth direction (panning), as well as the beam width of the antenna (fanning) remotely (see Figure 37). Figure 37 includes additional terminology associated with the beam control functionality of these antennas (1D, 2D, 3D and RET, RAB, RAZ).
3.2 USE CASES OF RECONFIGURABLE BEAM ANTENNAS IN 3G NETWORKS

Reconfigurable beam antennas can be used for multiple purposes, including coverage, quality, and capacity improvements. Several use cases are explored with a focus on load balancing capabilities.

To gain better insight into the real value of reconfigurable beam antenna technology, a radio planning analysis was conducted. Data was used from a 129 site, 3G UMTS radio network in Brussels, Belgium. The study utilized a commonly used radio network planning tool, including the planning data from the configuration data base that is geo data, operational target values, and traffic distribution statistics.

All base station and link budget-related parameters (power levels, operating frequencies, mobile service requirements, transmit and receive properties of the base station, as well as the mobile equipment, etc.) are based on typical examples used by operators to plan and optimize their UMTS radio network.

In general, radio networks can be limited by coverage, interference, or radio resources. Networks in the first phase of their life cycle (and deployment cycle) are typically limited by coverage or bad interference design.

In contrast, mature radio networks are typically limited by capacity and radio resources. A description of these is depicted in Figure 38. The maximum traffic load is indicated by the red line at the 100% mark. Since different base stations may use different radio equipment, and hence have different absolute capabilities for maximum traffic, relative numbers are shown.
Phase 1 shows the network where traffic demand due to mobile users in the network is very low. Networks are typically designed and deployed based on land usage information (clutter), as indicated in the color-coded clutter map on the top left-hand side in Figure 38. The loading of individual sectors is also well below the maximum traffic that can be handled in such cases. The network is typically limited by coverage and interference rather than capacity.

Phase 2 describes a more mature network where higher traffic demands occur. Once the number of subscribers and the data rates for the individual services increase, the cell utilization increases. This is shown on the bottom right-hand side of Figure 38. The traffic distribution in such cases is typically highly inhomogeneous within a network, which is indicated by the top right-hand side, color-coded traffic density map. This results in many cells with a low load, while other cells are overloaded, i.e., exceed the nominal limit of 100% maximum traffic load. An increasing number of blocked and dropped calls are the consequence, leading to significant additional infrastructure investments to handle the offered traffic.

Therefore, one of the key questions to be answered by the study is whether reconfigurable beam antennas can help balance the load between different cells, leading to a combination of coverage, interference, and capacity improvements.
3.3 COMPARISON OF RET, 2D, AND 3D RECONFIGURABLE BEAM ANTENNAS

To investigate the impact of Reconfigurable beam antennas on load balancing, we compared its performance with conventional antenna technologies, including RET antennas using the network and traffic scenario as shown in Figure 38, phase 2 as the starting position.

This is a 3G UMTS network with 65° antennas. The mechanical tilts are used from the underlying 2G network. The initial electrical tilts were set to 2°. This is a typical deployment coverage approach for a 3G overlay on an existing 2G network. Comparing three different reconfigurable beam antenna types and the range of parameters used for this simulation:

- RET antenna: Fixed 65° horizontal pattern, elevation range of the remote tilt [0° to 10°], no azimuth changes; \( \text{Tilting only} \).
- 2D Reconfigurable beam antenna: Fixed 65° horizontal pattern, elevation range of 0° to 10°, remote azimuth changes in the range of \([-30° \text{ to } +30°]\); \( \text{Tilting + Panning} \).
- 3D Reconfigurable beam antenna: Elevation range of [0° to 10°], remote azimuth changes in the range of \([-30° \text{ to } +30°]\), flexible antenna beam width in the range of [33° to 120°]; \( \text{Tilting + Panning + Fanning} \).

3.4 MEASUREMENT OF COVERAGE, INTERFERENCE, AND LOAD BALANCING WITH RECONFIGURABLE BEAM ANTENNAS

Reconfigurable beam antennas can provide multi-dimensional improvements in coverage, interference, and load balancing.

- **Coverage Measurement**
  - Pilot coverage
    Sufficient signal coverage on the pilot (also called common control or broadcast signal) is the basis for all wireless communications systems. The received signal strength of the pilot tone at the mobile has to exceed the receiver sensitivity to ensure that a mobile can connect to the network. Reconfigurable beam antennas can significantly help to increase the basic network coverage.
  - Service coverage
    Different services may require different received signal levels so that a successful service connection (a voice call or any data transmission) can be established between the mobile and the network. These service coverage requirements depend upon the received signal level and the received SINR.

- **Interference Measurements**
  - Improvements in C/I (Ec/lo)
Interference is one of the key limiting factors in wireless systems. In order to work properly, every data transmission requires a minimum signal to interference ratio. This is usually expressed in terms of carrier to interference ratio (C/I), or Ec/Io.

Improvements in the C/I (Ec/Io) result in better service coverage, services with higher data rate throughputs, and improved service quality in general. Improving the C/I (Ec/Io) also means that lower transmit power levels per connection are required for the same service, leading to significant improvements in the overall network capacity.

- Reduction in the cell overlap or “Soft Handover”

Cell overlap in CDMA type systems is required for a smooth handover for a user moving from one service cell to another, also called “Soft Handover.” As mobile devices in Soft Handover mode receive the same, hence redundant, information from multiple base station transmitters simultaneously, a large cell overlap leads to significant capacity reduction. Cell overlap should therefore be kept as low as possible, but necessary as required by soft handover.

Reconfigurable beam antennas can be used to control both interference, as well as cell overlap in a highly effective manner.

- Load Balancing Measurements

As shown in Figure 38 right-hand side, the distribution of the sector load is typically highly inhomogeneous within the network. While some sectors experience very high traffic loads, the utilization of the majority of the sectors is well below the maximum load.

- Measurement in sector utilization

In an ideal network, the maximum system capacity can be achieved by equally balancing load between individual sectors. This means that load from highly loaded sectors should be shifted to those that can easily handle additional traffic.

- Reduction of the number of overloaded sectors

The key benefit of load balancing is to allow for an increase in average sector utilization by reducing load on sectors that would otherwise become overloaded. This leads to significantly improved overall network performance and increased capacity utilization without additional radio channels, sectors, or cell sites thereby reducing or delaying CAPEX.

It will be shown that reconfigurable beam antennas enable flexible, cost-effective balancing of individual sector loads by allowing remote tilting, remote panning and remote fanning.

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1 Ec/Io = Average energy per chip over the total received power spectral density, including signal and interference in a CDMA system.
3.5 NETWORK OPTIMIZATION VERSUS LOAD BALANCING

Although various improvements can be achieved simultaneously, the performance improvements that are achievable depend upon the available degrees of freedom of the reconfigurable beam system.

Coverage and interference improvements can be considered as classical optimization tasks. The trade-off of capacity and coverage or coverage and interference levels have been considered for use in dynamic optimization.35

The results of load balancing are shown in Figure 39B, and include:

- Increase in sector utilization
- Reduction of overloaded cells

![Figure 39A](image1.png)

![Figure 39B](image2.png)

**Figure 39** – Simultaneous improvements achieved by RET, 2D reconfigurable beam, and 3D reconfigurable beam antennas.

In Figure 39A, the relative improvements in coverage, C/I (Ec/Lo), and reduction in the cell overlap are shown. In Figure 39B, the relative increase in sector utilization and reduction of overloaded cells are shown as compared to the initial scenario. While RET antennas are good for interference optimization and cell overlap reduction, their benefit for coverage improvements and load balancing are limited as compared to 2D and 3D Reconfigurable beam antennas.

Starting from the initial settings, different antenna technologies have been used for both network optimization and load balancing simultaneously. Improvements quantified by this study of a particular network and its associated environment and traffic pattern are summarized below:

- **Improvements by 1D RET antennas**
  a) **Optimization gains**: It can be observed that the key strength of RET antennas is the optimization of C/I (Ec/Lo) performance in a network (see Figure 39A). Cell overlap can be
controlled similarly to the interference in the network. However, in this case RET antennas have shown a limited ability to improve the coverage of the network.

b) **Load balancing gains**: As Figure 39B shows, RET antennas were not as effective for load balancing as were panning and fanning antennas. In this case, modifying tilt was obviously not sufficient to move traffic effectively from one sector to another. This resulted in a small relative improvement of cell utilization. As a result, the number of overloaded cells was only reduced slightly, see Figure 39B.

- **Improvements with 2D Reconfigurable beam Antennas**
  
  a) **Optimization gains**: In cases where 2D reconfigurable beam antennas were used, all optimization objectives were improved when compared to the RET situation. C/I (Ec/Io) and cell overlap performance have been improved, and the relative coverage improvement has more than doubled compared to the RET case. See Figure 39A.
  
  b) **Load balancing gains**: Since 2D reconfigurable beam antennas have the additional degree of freedom for remote changes of the boresight direction (panning), it is shown that the offered traffic can be shifted more effectively between the individual cells. This resulted in better load balancing, and higher cell utilization, hence the ability to reduce the number of overloaded cells significantly, as shown in Figure 39B.

- **Improvements with 3D Reconfigurable beam Antennas**
  
  a) **Optimization gains**: In addition to 2D reconfigurable beam antenna cases, the beam width of the antenna can be modified remotely (fanning). All of the performance indicators related to optimization were significantly improved compared to the 2D reconfigurable beam case. C/I and coverage were further improved. In this analysis, compared to RET antennas, C/I improvements were almost doubled.
  
  b) **Load balancing gains**: Since 3D reconfigurable beam antennas have the highest flexibility to balance the load between sectors, i.e., to shift traffic among the cells, the study indicated that the increase in the average cell utilization was boosted. This lead to a dramatic reduction in the number of overloaded cells, as shown in Figure 39B.

### 3.6 ANTEenna BEAM WIDTH DISTRIBUTION

Most existing wireless networks use a fixed choice for antenna beam width, that is, the 65° antenna which is the most widely used antenna pattern worldwide. In contrast, this analysis shows that significant gains can be achieved with the flexible beam width provided by the 3D reconfigurable beam antenna.

To give insight into the most appropriate antenna beam width, Figure 40 shows the statistical distribution of the antenna beam width using the 3D reconfigurable beam antenna from the cases in the previous sections. Two beam width distributions are shown for different traffic scenarios. The traffic scenarios are taken from different network cases in the morning and late afternoon, respectively.

From the first look, it can be seen that the “65° pattern fits all” maxim is no longer valid. It has already been shown from the results of the 3D reconfigurable beam antenna in Figure 40 that significant improvements of coverage, C/I (Ec/Io), as well as a large reduction in the number of overloaded cells, were achieved by the use of a flexible beam width.

A narrow antenna beam width results in a higher antenna gain in the main lobe direction, as compared to a wider antenna beam width with a significantly lower main lobe gain. This is one reason why a mixture of different antenna beam widths provides the best performance.
Figure 40 – Distribution of the antenna beam width after the optimization. Case 1 is morning and case 2 is afternoon. Distribution of the antenna beam width shown in Figure 40 shows some clusters around 45° and at the upper end above 100°. The distribution depends on various input parameters, such as the scenario itself, the traffic distribution, as well as the desired focus on the optimization objective, as indicated in the figure.

It may be speculated that wide beam width pattern will cause higher sector-to-sector interference. The results in Figure 39A show a different picture: The actual sector-to-sector interference was not significantly reduced by the use of variable beam width. This can be attributed to the fact that it is not just the beam width, but the combination of beam width and azimuth changes that provides substantial improvements.

3.7 RECONFIGURABLE BEAM ANTENNAS – CYCLICAL TRAFFIC PATTERN MANAGEMENT

Measurements in wireless networks show a clear daily cyclical behavior. An example for the traffic pattern of a single sector, over a 24-hour, 7-days a week period is shown in Figure 41. It can be observed that the traffic pattern repeats over time.
Keeping in mind that the overall traffic will grow over time, in general, the total traffic will be a combination of a cyclical pattern combined with an increasing average value.

By using smart RF technologies, such as SON, with reconfigurable beam antennas, wireless networks can remotely adapt to these continuously changing traffic situations. This adaptive, agile beam control technology has the potential for a positive impact on both CAPEX and OPEX for networks operators.

### 3.8 RECONFIGURABLE BEAM ANTENNA SUMMARY

Reconfigurable beam antennas have been shown to be a benefit for flexible wireless network management.

The following conclusions can be drawn from the specific network analysis case presented.

- RET antennas had a significant impact on the improvement of C/I and Ec/Io in CDMA based 3G radio networks.
- 2D reconfigurable beam antennas showed significant improvements in all performance indicators when compared to the Brussels network optimized with RET antennas. This includes coverage and C/I (Ec/Io) improvements, as well as higher cell utilization.
- 2D reconfigurable beam antennas allows for higher utilization by shifting traffic from overloaded sectors to those that can carry extra load, in this case, reducing the number of overloaded cells by up to 50%.
- 3D reconfigurable beam antennas generated the highest performance gains of all the reconfigurable beam antenna types. This was the case for coverage and C/I (Ec/Io) objectives, as well as for cell utilization and the balance of cell loads.
- In the case of load balancing capability and improvements, for this typical example, 3D reconfigurable beam antennas outperformed RET antennas by a substantial margin.
- The optimal distribution of the antenna beam width indicated that the singular use of a 65° pattern maybe far from ideal for wireless networks.
• In this case, reconfigurable beam antennas reduced the number of overloaded cells by approximately 80%. Higher utilization of existing sites, enabled by reconfigurable beam antennas, could reduce or delay future CAPEX and OPEX expenses for an operator.

• 3D reconfigurable beam antennas allow highly increased flexibility. With cyclically changing traffic patterns, a scheduled network adaptation has the potential to impact the quality and cost and cost of cellular network operation. Reconfigurable beam antennas, in combination with the network management systems are well suited for this application.

References of interest on reconfigurable beam antennas can be found in the endnotes.36,37

4 DEPLOYMENT SCENARIOS

Planning for future deployments of various smart antenna schemes requires an appreciation of the currently deployed legacy cell sites as does discussions of general deployment issues affecting operators.

4.1 TYPICAL CELL SITE ARCHITECTURE

A typical Cell Site consists of the components diagramed in Figure 42 below. This includes the power main and any wired backhaul facilities to the site, an AC to DC power rectifier and battery supply, and the eNodeB cabinets. These cabinets may be located in a shelter for weather protection or they may be outdoor units mounted on cement plinths. Backup diesel generators or other power sources may provide backup of one or more operators’ AC supplies. The eNodeB base station cabinet may contain the RF modulators, RF Power Amplifiers, duplexing filters, and lightning arrestors and serve antennas through long coaxial feeder cables as shown on the left tower, or it may distribute the RF components to positions next to the antennas as shown on the right figure with the use of the Remote Radio Heads (RRHs, also known as Remote Radio Units, RRUs). In this case, the eNodeB has a pair of fiber optic cables and power line connecting to the RRH that has the radio modem, power amplifier and filters for a sector, as shown on the right tower below where one sector’s equipment is shown in green.
Figure 42 – Components of cell site, highlighting a single sector’s tower equipment.

A photograph of a typical site with outdoor cabinets connected directly to the antennas with coaxial cables such as to the left is shown below in Figure 43.
Optionally, instead of RRHs, one may have tower-mounted Low Noise Amplifiers, and tower top power amplifiers may be used. On occasion, legacy base stations supporting one or another frequency band(s) with various air interfaces will sometimes be multiplexed with a newer base station equipment so as share the same cable and perhaps the same antenna system. When one antenna cannot support both frequency bands then duplex filters atop the tower may be used to direct the various bands to their respective antennas.
Increasingly, modern deployments use Remote Radio Heads (aka Remote Radio Units) that replace the bulky and lossy coaxial cables with lighter weight fiber optic cables (and DC power cables) that locate the amplifiers close to the antennas so as to reduce losses and the effective receiver noise figure. A typical installation is shown below. This installation supports multiple bands and multiple air interfaces. The panel antenna has two cross polarized columns at high band and one cross polarized column at low band.

Figure 44 – Tower view of a modern installation with several Remote Radio Units mounted behind the multi-band antenna.
4.2 CURRENT DEPLOYMENTS

One operator contributed that the percentages of various types of antenna placements are as given in Table 3. We see here that towers and monopoles are used extensively (59%) while rooftops account for about 19% of installations. As one might expect, rooftops are more commonly used in urban settings.

Table 3- National cell site categories (all towers include the 3 following subcategories of towers).

<table>
<thead>
<tr>
<th>Cell Site Types</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rooftop</td>
<td>19</td>
</tr>
<tr>
<td>All Towers</td>
<td>29</td>
</tr>
<tr>
<td>Self support</td>
<td>19</td>
</tr>
<tr>
<td>Guyed Tower</td>
<td>7</td>
</tr>
<tr>
<td>Utility lattice tower</td>
<td>3</td>
</tr>
<tr>
<td>Monopole</td>
<td>30</td>
</tr>
<tr>
<td>Water Tank</td>
<td>5</td>
</tr>
<tr>
<td>Others</td>
<td>18</td>
</tr>
</tbody>
</table>

In addition, these sites have the following numbers of antenna radomes per sector.

Table 4 – Number of antennas per sector.

<table>
<thead>
<tr>
<th>Antennas (Radomes) per Sector</th>
<th>Percentage of Sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.9%</td>
</tr>
<tr>
<td>2</td>
<td>61.0%</td>
</tr>
<tr>
<td>3</td>
<td>11.7%</td>
</tr>
<tr>
<td>4</td>
<td>0.3%</td>
</tr>
<tr>
<td>5</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

The average number of these antennas (radomes) is 1.9. Additionally, the majority of the sites have 3 sectors. Keep in mind that increasingly, multiple bands are supported within a single radome. And installations that once used to separate vertically polarized antennas in their own radomes may now use cross polarized elements within a single radome.
Knowing that about 30% of the deployments are on monopoles, it is worthwhile observing in the following figures the typical mechanical constraints atop a monopole where the structure provides a platform for positioning antennas, Remote Radio Heads, tower top amplifiers, LNAs, feeder cables, and the like, including workspace for installers. These pinwheels are typically placed no closer than 10 feet vertical separation. Notice the 16 feet of linear separation available for antennas sharing the same “sector face.” For an antenna configuration such as Antenna Configurations (H) or (I) (Div-2X or TX-DIV) in Figure 27, this corresponds to as much as $11 \lambda$ at 700 MHz.

Figure 45 – Tower top platform with typical dimensions.
The five operators sharing the leased monopole above all use coaxial cables to connect to their antennas, and all use similar triangular mounting platforms except for the second from the top. It uses struts such as those shown in Figure 47, below. Ropes for hoisting the antennas are still visible in this photo taken during installation in 2010.

4.2.2 TYPICAL MAST DEPLOYMENT

One can see in the photograph in Figure 46 above, that the second platform from the top is not a full “pinwheel” but a cantilevered strut assembly called a “pinwheel” and detailed below in Figure 47. These
platforms do not have the same workspace available as the full triangular platforms shown above but they can still use Remote Radio Heads and can be equipped with antennas spaced as far apart as those shown above.

Figure 47 – Typical monopole antenna installation as seen from above and with remote radio heads mounted on the monopole.

When antennas are mounted on a lattice mast the cabling appears as shown below in Figure 48. Clearly these cables add to the wind load of the tower.
4.2.3 TYPICAL ROOF-TOP DEPLOYMENT

Rooftop deployments promise much shorter cable runs as shown in Figure 49 below. However, it is often necessary to place the cabinets indoors on a separate floor for ease of access (elevators often do not go to the roof and so a crane would otherwise be required to place large equipment on the rooftop).
Items 1-3 of Figure 49 are three cross polarized antennas located at three corners of the roof, each placed on non-penetrating mounts (that do not penetrate the rooftop and hence do not threaten to cause a leak in the roof.) Item 4 is the base station cabinet and each antenna has a remote radio head mounted with it as shown in Figure 50.

Figure 49 – Typical rooftop installation with three sectors. The top scale spans 5 meters and the bottom 12 meters.
Due to the “data tsunami”, service providers are studying all avenues to meet their network needs. Furthermore, baring a sudden spectrum allocation by government regulatory bodies, the service providers must be able to meet this traffic explosion with little more than the spectrum already allocated. Heterogeneous Networks, or HetNet, is often touted as a means to increase network capacity within the confines of the spectrum already allocated. A large part of the HetNet paradigm is the “small cell” infrastructure that is envisioned as the means to greatly increase frequency reuse through higher density cell site deployments. At this time the small cell infrastructure market is very much unsettled with many non-traditional infrastructure vendors entering the small cell marketplace. For this reason the definition of a small cell is still very much in flux, but is certain to solidify in the coming year. In this section, an attempt is made to explain the coming role of small cells in the service provider’s network, give some thoughts on small cell deployments, and highlight the challenges of their deployments.

Market research firm, Infonetics Research, estimates that the global market for small cells (not counting residential femtocells) will grow to about 3 million units in 2016 worth approximately $2.1 billion. Their report states that 50% of small cell shipments in 2012 are for public spaces (as opposed to enterprise femtocells) with most planned for use in urban cores. The Americas (NAR + CALA) are estimated to account for 14% of current sales.

For the purposes of this white paper, and so as not to confuse a small cell with a more consumer-type access point like a residential femtocell, the following points will help define what is considered a small cell:

- Low power. Typically output power is 5 Watts or less.
- Small compact size.
- Indoor and outdoor deployable.
- Integrated baseband or traditional backhaul options.
• Must radiate in licensed bands, and may include unlicensed band, WiFi, operation.

• Integrated or external antenna.
• Directional and omnidirectional antenna options.
• MIMO ready.

As well, how the macro-cell and small cell network will interact and the ultimate benefit to the end user is beyond the scope of this document.

As previously mentioned, the HetNet strategy is mainly borne from the service provider’s need to expand their network capacity as ever increasing data traffic utilization thresholds are exceeded. As illustrated in Figure 51, in this scenario, small cells will be used to dramatically increase the cell spatial density within a geographic area with high user load to carry user traffic and offload the traffic from the traditional macro-cell network. Another small cell scenario envisioned is to play a role in the service provider’s arsenal to fill coverage holes in their macro-cell deployments. In this scenario the density of small cells should be far less than suggested in Figure 51.

![Figure 51 – Illustration of macro cell with small network cell under laid.](image)

It is envisioned that small cells will also allow for flexible deployment scenarios. Depending on the scenario and network needs a small cell could be affixed to the side of building, on the top of utility poles, on a cable strand, and with either directional or omnidirectional antennas. This is illustrated in Figure 52, which shows a small cell with omnidirectional antennas (a); (b) shows a small cell with integrated directional antennas affixed to a street light pole, and (c) an omnidirectional small cell affixed to a cable. Depending on the service provider needs, and small cell chosen, mechanical antenna tilt options may be offered, however, the compact size typically includes a pair of diversity antennas composed of single elements, so electrical tilting is not possible.
The exact nature of the small cell deployment is beyond the scope of this document, but the prevailing thought is the small cell location will be much closer to the user and hence much lower in the clutter environment than traditional macro-cell antennas. Service providers will have to consider this fact when deploying their small network deployment and optimization strategies. In the initial planning stages, this may require system and network level simulation tools to more accurately account for the building, clutter, and terrain surrounding the small cells. In addition, existing hotspots need to be identified geographically. This typically involves collecting call records and geolocating the connections, drops, and demand to be used to forecast where demand should be offloaded to small cells and with what urgency. While this may add complexity to the planning tools, this should be offset by better estimating cell placement and orientation for a wide scale small cell deployment.

There are numerous challenges in small cell deployments:

- Site acquisition: Beyond the well known site acquisition issues encountered in macro cell deployments, a HetNet deployment will require significantly more sites. The site acquisition process may have to be modified in a manner that is yet to be determined.
- Zoning requirements: active electronic placement closer to the end users may require additional concealment efforts and additional education of local zoning boards to facilitate acceptance in the community.
- Power and backhaul: each small cell obviously requires power, and backhaul to the service providers network. This is closely related to the site acquisition process, and tradeoffs may have to be made to facilitate backhaul connectivity with adequate site throughput.
• Interference/obstruction: as small cells are more easily placed in environments with which operators and installers are unfamiliar, new challenges reveal themselves. At these lower locations below the clutter, the local environment changes more rapidly as signs, awnings, facades, decorations, and even ladders and trucks move into and out of the deployment area. The uncoordinated placement of other radio products and even fluorescent lighting can cause RF interference and PIM generation. All of which add to the challenge of installing and maintaining these new small cells.

• Mass deployments: There is the potential for large scale deployment of small “metrocells” as a city may permit the installation on utility poles or bus stop shelters. There have been proposals for replacing old incandescent street lights with new, energy efficient LED based lighting along with integrated small cells. In this way, the overall power consumption for the city would be reduced while wireless connectivity improves.39

![Figure 53 – Concept for a streetlamp with integrated radio access metrocells. (Used with permission: Anne-Sofie Voss, Anders Backe and Troels Rask Pedersen)](image)

Partnering with utilities, municipalities, and other companies with access to urban furniture suitable for small cells is an important new business aspect of this new stage in the industry’s progression.

In the small cell ecosystem, there are vendor specific solutions (SON, interference mitigation, mesh networks, etc.) that are designed with deployment challenges in mind, and the marketplace will determine the widespread acceptance of these going forward.
Overarching issues of wind loading, zoning, and rental covenants apply throughout the various antenna deployment schemes. Operators often have lease agreements dating back several years that stipulate the number of cables, antenna dimensions, weights and loadings, and so forth that would have to be renegotiated at more restrictive terms if configurations were to be changed. While these restrictions are not universal, they can constrain the adoption of smart antennas and 4G mobile broadband systems. To install a larger antenna or RRH, an operator may have to pay for a new engineering study of the weight and wind load on all relevant structures, for example, adding considerable expense to an upgrade.

6.1 CONSTRAINTS ON THE ANTENNA DEPLOYMENTS DUE TO COMMERCIAL CONSIDERATIONS

Standard lease agreements for the placement of antennas, cables, and wireless equipment have become increasingly restrictive. For example, a typical publically available municipal lease agreement requires:40

1. Setback should be 300%, so a 30 m tower should have a 90m setback from the property line.

2. Panel antenna no more than two feet (2’) wide and eight feet (8’) long, extending above the structure to which they are attached by no more than ten feet (10’). Some operators and zoning issues restrict size to even less, say, 1 foot by 6 feet.

3. Antenna, antenna array, and support structures not on publicly owned property, shall not extend more than ten feet (10’) above the highest point of the structure on which they are mounted. The antenna, antennas array, and its support structure shall be mounted so as to blend with the structure to which the antenna is attached. The antenna and its support structure shall be designed to withstand a wind force of one hundred (100) miles per hour without the use of supporting guy wires. The antenna, antenna array, and its support structure shall be a color that blends with the structure on which they are mounted.

We have seen in other similar lease agreements restrictions specify that the overall loading on towers be restricted to less than 85%, but leave it to operators to improve the site or mast to support any additional loads.41

These restrictions on antenna form factors are further constrained by the aesthetic judgments of zoning commissions and other municipal boards and property owners. Moreover, installation costs increase substantially if cranes are needed when hoists are insufficient. In order to standardize configurations some tower managers have stipulated that antennas and other equipment mounted on a mast or tower weigh in the range of 20 to 30 pounds for each such entity, for ease of hoisting and positioning by a single climber. The range of sizes can be in the 0.75 to 1.5 foot wide by 5 to 10 inches deep by 70 to 100 inches tall, which can be a severe limitation on the antenna scheme used. For example, a 4 column array of vertically polarized antennas spaced at \( \frac{\lambda}{2} \), which at 750 MHz (band class 13) takes a width about 2.6 feet.

Rooftop installations typically restrict the height of towers above the roofline, the mounting of rooftop equipment on non-penetrating plinths (so as not to cause the roof to leak rainwater). Also zoning and aesthetic considerations are limiting the visual impact of the antennas. This impacts not only their
coloration (to look like trees, for example) but also their overall area. Even in India and China, there are field reports of having to remove 8 column antenna arrays because of their visibility.

6.2 ELECTRICAL AND MECHANICAL TILTING OF ANTENNAS

6.2.1 EFFECTS OF MECHANICAL DOWNTILT ON SECTOR ANTENNA HORIZONTAL PATTERNS

Background

Cellular Networks achieve large capacity capabilities by re-using given frequencies repeatedly in a given system. This concept means that the communication paths are interference limited as opposed to traditional radio systems that were noise limited. To minimize interference, the use of sectorized antennas have been employed, each of which provides coverage to a portion of the cell. In a 3-sector arrangement, each sector antenna covers a 120° pie shape that extends some distance away from the antenna site. Likewise, for a 6-sector site, each antenna covers a 60° pie shape.

The cellular concept presents system designers with some challenges. Ideally, each sector antenna should only provide coverage in its 120° pie shaped sector so that interference with adjacent sectors is minimized. Often, the elevation beam is tilted downward to minimize interference with other cell sites. However, in both cases, there must be enough coverage overlap to facilitate high-speed handoffs so that calls are not dropped during the handoff process.

Antenna designers go to great lengths to develop sector antennas that have characteristics such as fast azimuth pattern roll off past the 3 dB points, high front-to-back ratios and excellent upper side lobe suppression on the elevation patterns. All of these features help to minimize harmful interference.

Traditional voice networks have been shown to be fairly tolerant of interference since voice conversations are still intelligible even with an occasional interference burst causing a few percent BER. However, with the introduction of high-speed data networks, optimizing the desired-to-undesired signal ratios will become a prime consideration and optimized sector antenna patterns can provide great benefits.

Network Optimization

As networks were built out, it was found that the distance covered by various sector antennas had to be adjusted because of unwanted interference. Issues like terrain coverage, non-optimal site location, and capacity driven cell splitting are some examples. Several choices were available to accomplish this including lowering the antenna height, changing to an antenna with lower gain or down tilting the elevation beam of the existing antenna – either mechanically or electrically. The latter option was usually the most cost effective and has been heavily used. This down tilting lowered the gain as viewed on the horizon since this is the area where interference takes place. The various tilted elevation patterns of Figure 54A and Figure 54B demonstrate how gain on the horizon – noted by the dashed line – changes with beam down tilt. This paper defines the yellow horizontal pattern cut as the one taken through the dashed line, while the orange azimuth pattern cut is the one taken through the peak of the elevation beam.
However, there are some important differences between mechanical and electrical down tilt. Figure 55A shows the results of a mechanically down tilted antenna where the main beam is tilted down at bore sight, tilted up at the 180° point behind bore sight and not tilted at all at the ±90° points. Figure 55B shows the results for an electrically tilted antenna where the tilt is the same at bore sight, the ±90° points and 180° point. This leads to some important differences when viewing the horizontal pattern cut.

Those differences in the horizontal pattern cuts are shown in Figure 56A and Figure 56B. As expected, the mechanically down tilted antenna’s gain is reduced at bore sight, but interestingly it is not reduced at all at the ±90° point. At small values of down tilt, the pattern seems acceptable but with greater amounts of down tilt the pattern takes on a “peanut” shaped look. This is undesirable since the purpose of down tilting is to reduce the coverage in all directions. As the better alternative, the electrically tilted antenna with its gain is reduced in all directions as shown in Figure 55B.
Figure 55—Differences between mechanically down tilted and electrically tilted antennas.

Figure 56 — Differences in the horizontal pattern cuts.

Even though the mechanically tilted antenna’s horizontal pattern cuts look acceptable at small values of down tilt, a subtle difference is taking place – commonly referred to as pattern blooming. In essence, the 3 dB beam width is getting larger. Blooming patterns become important from an interference standpoint because they increase the gain at the sector crossover points and they increase the sector overlap angle.
The widely used 65° azimuth antenna yields a typical 10 dB crossover gain and this has become the de facto specification for most modulation schemes in high capacity areas.

<table>
<thead>
<tr>
<th>M( )E( ) Tilt</th>
<th>Angle</th>
<th>Crossover</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0E0 &amp; M0E7 ----</td>
<td>17°</td>
<td>10 dB</td>
</tr>
<tr>
<td>M7E7 --------------</td>
<td>25°</td>
<td>6 dB</td>
</tr>
<tr>
<td>M14E0 --------------</td>
<td>29°</td>
<td>4 dB</td>
</tr>
</tbody>
</table>

Figure 57 — Minimal horizontal pattern change using electrical down tilt only.

In Figure 57 the Legend Table shows the value of mechanical tilt as M=[tilt value] and the value of electrical tilt as E=[tilt value]. Note that the normalized dark green pattern for E0_M0 and the light green pattern for M0_E7 practically overlay each other. This substantiates the concept of minimal horizontal pattern change using electrical down tilt only. The other normalized patterns of Figure 57 also show that when mechanical down tilt or combinations of mechanical and electrical down tilt are employed that the blooming becomes an issue. To determine the overlap angles, this example used a 6 dB differential as a method of comparison. This overlap can contribute to interference in time division multiplex systems and pilot pollution in code division multiplex systems.

In the past, a rough rule of thumb emerged that allowed system designers to determine what amount of mechanical down tilt could be considered acceptable based on blooming of 10%. The rule stated that an antenna should never be mechanically down tilted more than one-half of its vertical beam width. However, this rule did not take into account the fact that the antenna may also incorporate electrical down tilt.

**Combined Mechanical and Electrical Down Tilt**

Initiated by customer complaints about bad interference at a site employing both mechanical and electrical down tilt, an investigation was opened to analyze the effects of combined mechanical and electrical down tilt. This combination of tilts modifies what was shown in Figure 55B with results shown in Figure 58. It shows that the horizontal gain is reduced at bore sight, somewhat reduced at ±90° and actually increased at 180° compared to the pattern having only electrical down tilt. Similar to mechanical-
only down tilt, the horizontal pattern’s uneven gain reduction across the sector again causes blooming to occur. The challenge was to come up with a new rule of thumb that could predict the percentage blooming for a particular antenna given the electrical and mechanical down tilt settings.

First, range patterns were measured on different antennas for both the azimuth (through elevation bore sight) and horizontal (on the horizon) cuts. This was done at various mechanical and electrical tilt angles. The findings showed that the old rule of thumb was no longer applicable when electrical down tilt is employed.

Next, a mathematical model was developed that fit the measured data points and curves were generated showing the typical amount of combined mechanical and electrical down tilt allowable for 10% and 20% blooming. Some typical results are plotted as a function of the antenna’s elevation beam width in Figure 59.
As these curves demonstrate, the green 10% blooming line is a function of both mechanical and electrical down tilt. The more electrical down tilt is employed in an antenna, the less mechanical down tilt can be used to stay within the 10% goal. It is interesting to see that when these two different antennas are normalized using their vertical beam widths, the blooming percentages track very closely. This mathematical model has been used on a series of antennas and the blooming percentages track very closely.
closely. From these plots, a new rule of thumb has been developed for the common 65° azimuth beam width antennas. It states:

$$65° \text{ AzBW } M-\text{tilt}_{10\% \text{ Bloom}} = \frac{\text{VBW} - E-\text{tilt}}{2.5}$$

More accurate range data shows that even with no electrical down tilt the maximum mechanical tilt for 10% blooming is no longer half (50%) the vertical beam width but that it is the vertical beam width divided by 2.5 (40%). When large amounts of electrical down tilt are employed, acceptable mechanical down tilt can be limited to as little as 10% (or less) of the vertical beam width.

Another caution should be noted when using ultra-high gain antennas that incorporate electrical down tilt. It is extremely important to mount them exactly plumb to minimize any possible blooming. For instance, an antenna having 4° elevation beam width and 2° of electrical down tilt suffers 10% horizontal pattern blooming with less than 1° of mechanical down tilt!

Further investigation of antennas having azimuth beam widths different than 65° showed that their blooming did not follow the rule above. After checking several different azimuth beam width models the graph of Figure 61 evolved.

Figure 61 shows that the k-factor, which is 2.5 for 65° azimuth models, ranges from 1.5 for 33° azimuth models to 3.3 for 90° azimuth models. Note that these rules of thumb describe typical band-center performance and can vary somewhat at the band edges. They also only hold true if the combined mechanical and electrical tilts do not tilt the pattern beyond its first upper null.

![Mechanical Down tilt Factor for 10% Horizontal Blooming](image)

Figure 61 — Variations in the k-factor which is 2.5 for 65° azimuth models ranges from 1.5 for 33° azimuth models to 3.3 for 90° azimuth models.
Recall that the new rules of thumb are most accurate near the band-center of the antenna’s specified frequency range. They are also most accurate at the lower portion of the electrical down tilt range. In addition, the combination of electrical and mechanical tilt should never go beyond the first upper null of the elevation pattern.

Further Findings

In addition to horizontal pattern blooming, several other important antenna specifications were seen to degrade with mechanical down tilt. These include squint, front-to-back ratio, and cross-polarization ratio. Unfortunately, these are not easily mathematically modeled like the blooming issue. The following results from a relatively small number of antennas have been extracted from actual measured data.

Horizontal Beam Squint

Squint is defined as the difference between the mechanical bore sight and the electrical bore sight of an antenna as shown in Figure 62. The mechanical bore sight is defined as being perpendicular to the antenna’s back tray while electrical bore sight is defined as the mid-point of the 3 dB beam width.

![Figure 62 – Horizontal beam squint. (Note the approximately 10º clockwise rotation of the beam compared to the mechanical bore sight.)](image)

The previous figure illustrates how squint stays relatively constant for both vertically polarized (V-pol) and Dual-pol (X-pol) 65° models when electrical tilt is varied while mechanical tilt is fixed at zero. Figure 63 analyzes the same antenna models but now mechanical tilt is varied while electrical tilt is fixed at zero. The data is once again presented as a percentage of the antennas’ vertical beam widths for easy comparison. It shows that squint on X-pol antennas degrades with mechanical down tilt to the point that it can be greater than 10% of the antenna’s azimuth beam width at high angles of mechanical down tilt.
Sector Power Ratio

Sector Power Ratio (SPR) is another measure of an antenna’s ability to minimize unwanted interference in a cellular network. Figure 64 graphically shows the concept along with the equation used to calculate SPR. In essence, it compares the undesired RF power outside of the sector to the desired RF power within the sector and expresses it as a percentage. Excellent antenna designs provide SPRs as low as 3% to 4%, while traditional dipole or patch element designs can yield SPRs approaching 8%.

Figure 65 shows that similar to squint, SPR remains relatively constant for both V-pol and X-pol models as the electrical tilt is varied while keeping the mechanical tilt at zero. In Figure 66 SPR is shown to degrade significantly for all types of antennas when mechanical tilt is varied while keeping electrical tilt fixed at zero.
Figure 64 -- Graphical representation of Sector Power Ratio (SPR).

\[
SPR(\%) = \left( \frac{\sum_{i=1}^{300} P_{Undesired}^{i}}{\sum_{j=1}^{300} P_{Desired}^{j}} \right) \times 100
\]

Figure 65 – SPR remains relatively constant for both V-pol and X-pol models as the electrical tilt is varied.
SRP degrades significantly for all types of antennas when mechanical tilt is varied which keeping electrical tilt fixed at zero.

Front-to-Back Ratio and Cross-pol Ratio

When either (or both) of these two specifications degrade, system performance can be affected – but in different ways.

Front-to-back ratio (F/B) is traditionally measured by comparing gain at bore sight to gain at point 180° behind bore sight as shown in Figure 67A. Some system specialists have taken this concept to another level by characterizing the F/B ratio over some angle around the 180° point – such as 180 ±30°. Either way it is a measure of unwanted interference behind the desired sector.

Cross-pol Ratio (CPR) as shown in Figure 67B is a measure of the de-correlation of the two polarizations used in a X-pol antenna – one at +45° and the other at -45°. Within the sector, having gain de-correlation of at least 10 dB assures good uplink diversity in a multipath environment. Most cellular systems depend on some sort of receive diversity at the cell site to balance the uplink path from the lower power cell phone devices with the downlink path from the higher power cell site transmitters. Lack of good uplink diversity in essence shrinks the coverage distance of the site.

It should also be noted that for X-pol models, the total F/B power is the sum of the co-pol energy plus the cross-pol energy.
To demonstrate the huge amount of degradation that can happen to both F/B ratio and CPR when mechanical down tilt is applied to an antenna already having a large amount of electrical down tilt, the measured patterns of Figure 68 are presented. The patterns are for a typical 4 foot, 65° antenna employing 15° electrical down tilt along with 5° mechanical down tilt. The co-pol pattern is shown in blue and the cross-pol pattern is shown in red. With a vertical beam width of ~16° at 850 MHz, the tilt combination is well beyond even the 20% blooming curve of Figure 59. In fact, the horizontal beam width is in the neighborhood of 160° or approximately 250% blooming!

The F/B ratio has degraded to approximately 18 dB at 180° and the cross-pol is actually worse than the co-pol pattern. Taken over a ±30° angle around 180° this F/B method measures only 8 dB!

Finally, the CPR over the desired sector degrades to only 5 dB at the sector edge – far short of the 10 dB expectation.
Conclusions Concerning Electrical and Mechanical Downtilt

The industry has always realized the coverage and interference compromises associated with mechanically down tilting sector antennas and a rule of thumb commonly used to minimize these issues; however, it did not incorporate the use of electrical down tilt.

This sector analysis goes into more detail by showing how various parameters including horizontal beam width, squint, Sector Power Ratio, front-to-back ratio, and cross-pol ratio are all affected by mechanical down tilt.

It presents new rules of thumb that limit blooming to approximately 10% when combined mechanical and electrical down tilt are employed. Also included is measured data showing how the other important parameters mentioned above – especially for the popular Dual-pol® (X-pol) models – degrade when mechanical down tilt is used.

As the industry evolves toward data systems supporting higher and higher data rates, more attention must be paid to these parameters, which can severely degrade overall network performance, and the importance of using only electrical down tilt.
6.2.2 EFFECTS OF INCORRECT ANTENNA INSTALLATION

Background

As was stated in the previous section, cellular networks re-use frequencies repeatedly again to achieve the capacities demanded by today's customers. In order to achieve optimum performance the sectorized antennas used at each cell site must be installed according to the design engineer's specifications. If they are not installed correctly, network performance will suffer.42,43

Real World Issues

Many installers who have the dangerous job of climbing cellular towers have not been properly trained on the importance of correct antenna installation. Some common issues are noted below:

The antenna support pipe must be plumb. Often installers will mount an antenna such that it is parallel to the support pipe. Of course, if the support pipe is not plumb, the antenna will not be plumb. This can produce mechanical downtilt, mechanical uptilt, or side-to-side skew depending on the support pipe's orientation. The correct procedure is to use a digital inclinometer to plumb the antenna in both planes using the adjustable mounting brackets supplied with most sector antennas.

The azimuth pointing direction is not correct. The design engineer specifies a geographic pointing direction or heading for each antenna to insure optimum network performance. However, if care is not exercised, a couple of issues can cause serious problems. First, magnetic compasses do not read correctly when used near a large amount of metal and since towers use large amounts of metal, readings taken at or near the antenna will be faulty. Usually it requires someone on the ground – away from metallic structures – to establish the correct pointing direction and coordination with the installer on the tower to then point the antenna correctly. The second issue that untrained installers encounter is the magnetic declination angle between magnetic and geographic North. In some areas, differences greater than 15 degrees exist. To complicate things even further, the declination changes from year to year so it is important that installers know where to access the latest information.

Azimuth adjustment tools are available on the market that makes use of relative bearing references to known large objects, such as churches, chimneys, and silos, rather than magnetic compass bearings. Relative bearings can be obtained from a map and then used as a reference for the azimuth adjustment tool while adjusting the antenna azimuth direction.
The mounting hardware must be assembled correctly. Antennas either are supplied with mounting kits or have them available as a separate purchased part. If the installer does not follow the installation instructions, some of these mounts have been known to change position under high wind conditions. The network will suffer until another tower climb is initiated to repair such a faulty installation.

6.3 PASSIVE INTERMODULATION (PIM) SITE CONSIDERATIONS

6.3.1 BACKGROUND

Intermodulation is defined as the mathematical mixing of two or more desired RF signals to generate a family of undesired RF signals. For years, this phenomenon has been well understood in active components such as power amplifiers and preamps. With the introduction of duplexed, high data rate systems the industry has become focused on this same intermodulation happening in passive RF components – especially those that share both downlink (high power transmit) and uplink (very low power receive) signals. If undesired passive intermodulation (PIM) products are produced in the receive frequency band of an FDD system, there is no way to eliminate them by filtering signals and they will interfere with or degrade the desired signals coming from user equipment (UE).

6.3.2 DISCUSSION

Intermodulation can take place whenever multiple RF signals encounter some type of non-linearity. It can take place in the RF path or beyond the RF path after the signals are radiated from the antenna. Things such as rusted tower joints or guy wires as well as rusted or corroded equipment on a building top are all examples of PIM generators. Loose nuts and bolts or rivets are other examples.

All RF path components such as connectorized transmission lines and jumper cables, antennas, diplexers, tower mounted amplifiers (TMAs) etc., have some inherent degree of non-linearity. The industry’s challenge is to develop designs that suppress the unwanted intermodulation to acceptable levels. The accepted standard for antenna PIM uses two 20 watt transmitters (A and B) and states that
any third order intermodulation products (2A-B or 2B-A) must be at least 150 dB below the two transmitter carriers (-150 dBc).

Another type of third order intermodulation product takes the form of $A + B - C$ where three desired signals are now involved. It also opens up the possibility that different frequency bands and blocks can be involved. This type of PIM can happen when diplexers are used to minimize the number of transmission lines at a site. For instance if a US operator had PCS blocks B and F and decided to diplex them with the Upper 700 C block, there is a possible PIM hit ($756+1973-1952=777$). A calculator is available that allows designers to check for PIM problems when various band(s) and block(s) are combined. It is strongly recommended that these combinations be avoided since they are very difficult to eliminate in practice.

Other less complex components like connectorized transmission lines and jumpers normally are specified to have better PIM suppression in the range of -160 to -163 dBc. This is important since in the complete RF path there will be a number of PIM generators and the system PIM will depend on all of the contributors. Each PIM contributor is a vector having amplitude and phase so they can combine in various ways. The typical result is a random combination of the individual vectors, but under worst-case conditions, they could all combine in-phase.

### 6.3.3 TESTING CONSIDERATIONS

There are several test equipment companies that have developed rugged, high performance, portable PIM test equipment. Most can test either throughput PIM or reflected PIM. Since the industry is concerned about PIM coming back into the receivers, most components are tested for reflected PIM. This equipment must be complimented with a good low-PIM 50-ohm test load and a good low-PIM jumper cable before meaningful testing can be done. Testing two-port devices like coax cables for reflected PIM is relatively straightforward and simply requires that the low-PIM load be connected to the output port. Be sure to correctly torque all RF connectors. However, testing antennas for PIM is a much more meticulous process. For best results, the antenna should be tested outdoors facing skyward with no metal within 15 to 20 feet. Testing indoors, even in large warehouses, should be avoided as these environments have shown to produce incorrect results. In addition, no personnel should be close to the antenna during testing. Items like keys in someone’s pocket or a cell phone on their belt can cause undesired PIM. Again, applying the correct torque to RF connectors is an important step.

For field-installed connectors on transmission line or jumper cables, use of the recommended cable preparation tools is very important. Follow the manufacturer’s instructions closely to insure the best results. Smooth flared surfaces with no burrs on either the center or outer conductor is required for low-PIM connectorization.

Finally, use only 7-16 DIN style connectors on all RF path components where possible. It is important that the connectors being used are approved for the cable brand being used to ensure the correct fit and sealing. Also, insure that the installers have the correct 25 Nm (222 inch-pound) torque wrenches.

### 6.4 INDEPENDENT ANTENNA TILT OPTIMIZATION BY AIR INTERFACE

It is common for operators that have multiple air-interface technologies in their network to elect to optimize the services independently. For example, an operator who is utilizing GSM in the PCS band and UMTS in the AWS band may elect to use two separate variable electrical tilting antennas rather then...
duplexing the services on one antenna. This approach is chosen even though the use of one antenna could have advantages for wind loading, leasing costs, and feeder cable reduction. Often quad antennas are used for independent tilt to minimize the radome count on the tower. Likewise an operator who deploys a multi-band antenna using GSM on the cellular band and UMTS on the PCS band can implement independent tilt to optimize the two services and associated frequency band separately. This independent tilt is particularly important for multi-band antennas given the relative differences between 1 GHz and 2 GHz for RF propagation, antenna gain, and vertical beam width.

As described in §1.4.1, novel new active antenna arrays are emerging that allow for the phase and amplitude weighting of signals on all antenna elements, not just columns of elements. This enables beam forming and MIMO operations in both the azimuth and now the elevation direction. Moreover, this can be done on a per carrier basis, or even on a per user basis.

With proper support in the baseband processing, these Active Antenna Systems can conceivably tilt different air interfaces on different carriers in the same band by different amounts. This can be particularly attractive for introducing LTE for hot spot coverage, where GSM/GPRS/EDGE or WCDMA/HSPA is tilted up for broad coverage while LTE is focused down at the local vicinity.

### 6.5 REMOTE RADIO HEADS FOR MIMO

Remote radio heads (RRH), also known as remote radio units (RRU), are currently being deployed not just for new technologies (such as LTE) but also in new and replacement infrastructure using older technologies (2G, 2.5G, 3G), primarily for reasons of lower capital and operating expenditures. The deployment of remote radio heads is accelerating as system operators become more comfortable with the reliability of the equipment, and are prepared to move the transmit and receive electronics close to the antenna(s) in each sector. In some cases, where there is not high confidence in the reliability or for other reasons, RRHs are deployed at ground level and traditional coaxial feeders are used to connect to the antenna(s). These ground level remote radio heads are also called transmitter-receiver duplexer units or TRDU, also known as a Radio Unit (RU).

#### 6.5.1 REMOTE RADIO HEADS AND TRANSMITTER-RECEIVER DUPLEXER UNITS

The major components of an enhanced Node B (eNB) include the transmitters and receivers (transceivers), power amplifiers, duplexers, antennas, low noise amplifiers (LNAs), operations and management (OA&M) controllers, antenna controllers, and baseband processing units. Traditionally the majority of the components of an eNB reside in a shelf at the base of the tower. RF cables are used to connect to the antennas at the top of the tower.

**Transmitter-Receiver Duplexer Unit**

The TRDU is a shelf-mounted module that integrates several functions of the eNB and is typically located near the base band unit in the eNodeB cabinet. In a typical implementation, the TRDU includes the transceivers, power amplifiers, antenna controllers, and duplexers. The TRDU is connected to the baseband processing unit via a high-speed optical serial interface and connected to the antenna via RF cabling. Forced air-cooling is employed in the eNB shelf.

**Remote Radio Head (RRH)**
A RRH, also known as a Remote Radio Unit (RRU), incorporates much of the same functionality as a TRDU. However, the RRH is a pole-mountable, weatherized, self-contained module that uses natural convection cooling. In a typical installation, the RRH is installed close to the antennas at the top of the tower with minimal RF cabling.

Figure 70 shows the block diagram of a TRDU/RRH with two transmitters and four receivers. The interface to the baseband processing unit is a high-speed optical interface (here a CPRI interface is shown). The interface board in the Figure incorporates some of the control functions such as antenna control (AISG) and alarming.
6.5.2 REMOTE RADIO HEAD ADVANTAGES AND CONSIDERATIONS

Remote radio heads have several advantages over traditional Node-B architectures.

- Site Footprint--Since they are mounted directly on a pole, they require little or no site footprint. This can significantly reduce capital expenditure by reducing site planning and maintenance costs.

- Power Consumption--The proximity of the transmitter to the antenna can minimize feeder cable losses and thus improve the overall base-station power consumption.

- Receiver Performance--The proximity of the receivers to the antennas also improves the sensitivity and noise figure of the receivers.

- Flexible Network Coverage--Limited site space availability in some areas can prevent the installation of a traditional BTS. An RRH can fill such coverage holes.

- MIMO Capability--The gains, phases, and delays of each individual carrier and/or the composite signal in each transmitter and receiver in a RRH can be digitally adjusted. Each RRH also has a measurement receiver that is used to calibrate the digital pre-distortion algorithms. The measurement receiver can be used to make accurate measurements of the gains, phases, and
delays of each transmit path. These features enable easy implementation of MIMO and SIMO processing architectures with RRHs.

- Daisy-chaining RRHs—Multiple RRHs can be daisy-chained using the optical interface and programmed to operate in a coordinated manner. This feature can be used to increase site capacity and coverage. It can also enable higher order MIMO and SIMO systems. For example, an RRH with two transmitters and two receivers can support a 2x2 MIMO system. Daisy chaining two such RRHs can enable a 4x4 MIMO system.

- Reliability—RRHs and TRDUs are inherently more reliable than traditional eNBs because of the integration of several subsystems in a single functional unit. RRHs, which are convection cooled, are less reliable than TRDUs, which are cooled using forced air. Innovative thermal designs and highly efficient amplifier designs have significantly improved the reliability of RRHs.

- Installation—A typical RRH can weigh 15-20 kg. Rooftop installations of RRHs are simple and straightforward. Tower-tops installations are more complex and require planning for tower climbs.

- Weatherization—Unlike a sheltered shelf, RRHs are exposed to the elements. Damage, performance degradation, and failures can result from improper mechanical design. Therefore, careful thermal and mechanical design is required to ensure proper weatherization.

- Battery Back-ups—Though an RRH can be installed at the top of a tower, battery back-ups will still be required for emergency operation. Most battery back-up systems will require some site footprint. Innovative solutions for the installation of battery cabinets near the RRHs are now available.

### 6.5.3 REMOTE RADIO CONFIGURATIONS.

Currently, RRHs are being deployed in multiple frequency bands, across several power levels and in various configurations.

**Frequency Bands**

UMTS (Node B) RRHs are commonly deployed in 2100 MHz and 900 MHz. RRHs to support the LTE trials in North America have been deployed in the 700 MHz and 800 MHz bands. Several LTE deployments in 2600 MHz are also underway. Additional frequency bands with early LTE deployments include 1500 MHz in Japan and 2300 MHz and 1.8 and 2.3 GHz in China with TDD-LTE installations.

The bandwidth of operation of the Remote Radio Heads is typically limited to 20 to 30 MHz in which multiple carriers can be located.

**Power Levels**

Macro cell installations with transmitter powers ranging from 10 Watt – 60 Watt are most common in initial deployments. Micro cell installations with power levels per transmitter ranging from 1-5W shall follow the macro cell installations. Multiple transmit ports typically divide the overall transmit power so there are 1 TX x 60 Watt and 2 TX x 40 Watt units as well as 4 TX x 10 Watt units.

**Transmitter-Receiver Branches**
At 700 MHz a 2x2 configuration (two transmitters and two receivers) is most common. A 2x4 configuration is preferred at higher frequencies like 2600 MHz, 2300 MHz, 1500 MHz, 1800 MHz, 1900 MHz, and 2100 MHz. As described earlier, multiple RRHs can be combined to form other configurations such as 4x4 and 4x8. At 2300 MHz, an 8x8 installation for TDD-LTE is expected to be widely deployed.

**Air Standards/Multi-Standard**

Currently RRHs are widely deployed in all major air standards such as GSM, CDMA2000, UMTS, WiMAX, and LTE. Most RRHs will be capable of supporting multiple air standards in one unit. Common multi standard implementations include LTE+UMTS, LTE+CDMA2000, or LTE+UMTS+GSM. An LTE+CDMA2000+UMTS configuration is expected to be less common. RRHs shall be software configurable and capable of supporting any carrier combination with these multiple standards.

**Interface Standard**

The optical high-speed serial interface between the baseband processing unit and the RRH/TRDU typically use the Common Public Radio Interface (CPRI) standard or the Open Base station Architecture Initiative (OBSAI) standard. Current RRHs support data rates up to 6.144 Gbps. It is expected that the next generation of RRHs will require line rates up to 12.2288 Gbps or higher.

This data rate on the high-speed serial interface reflects the maximum bandwidth of the spectrum transmitted and received by the Remote Radio Head/Unit as well as the number of branches, and the number of units that may be daisy chained with one optical high speed interface.

**FDD vs. TDD**

Most RRHs deployed support FDD (Frequency Division Duplexing). However, RRHs also support TDD (Time Division Duplexing) for WiMAX (licensed and unlicensed bands) and LTE (2300 MHz).

**Efficiency**

The efficiency of an RRH is defined as the RF output power delivered divided by the DC input power. At macro power levels, the power amplifier is the largest contributor to the overall power consumption of the RRH. This is not to say that the power consumption in the other subsystems is negligible. The power consumption in the digital subsystem can be significant (20-30 W) and this is especially critical for micro RRHs.

### 6.6 CABLE TRADEOFFS FOR REMOTE RADIO HEADS

A perennial challenge in placing antennas at appropriate heights has to do with the costly, bulky, and lossy coaxial cables. There are often many tens of meters of cable connecting the antennas and the radio transmitters, which are often located in climate-controlled enclosures on the ground near a tower base or in a central location either on the roof of a building or on a lower floor.

So-called “hard line” coaxial feeder cable is typically 7/8” to 1-5/8” or even thicker is used for long straight runs, such as up a tower, with more flexible and thinner jumper cables making shorter connections to the antenna itself on one end and to a lightning arrester and the base station on the other end. These cables along with their connectors, lighting arresters, and sometimes combiners, often contribute 2.5 to 3.5 dB of RF power losses, requiring an amplifier twice as powerful (and consuming twice as DC power) as strictly
required at the antenna. In addition, these cables add weight and wind load to a tower or mast installation.

In contrast is a remote radio head installation. The remote radio heads use fiber optic cable, either single-mode or multimode, for the transmit and receive signals, and they require power of course. The power is typically 48V DC, but some equipment is AC powered. Installed systems to date have used separate fiber and power cables, often installed in conduit for mechanical protection and electro-magnetic shielding against lightning strikes.

Here we compare the relative weight and wind load of Remote Radio Heads (RRHs) as opposed to running coaxial cables up a mast. For example, we consider the weight and wind load for a 4 branch per sector installation on a 30m mast**. Using the common 1-1/4” LCF114 cable, three sectors would contribute over 310 kg of mass on the tower or 680 pounds. Cable strain relief mounting hardware placed the recommended 4 feet and cable hoist add a minimum of 20 kg depending upon the type of hardware used. The sum total static load on the 30m tower is therefore at least 330kg (727 lbs). A remote radio head, on the other hand, typically weighs about 17 kg but with mounting hardware, power and fiber takes about 25kg, which is 13 times smaller than the coaxial cables that the RRH can replace. Two branches per sector would of course have half this weight or 155kg and would mean that the 2 cables per RRH would weigh over 6 times that of the RRH.

Cables are typically run up a mast along a cable run with stress relief clamps that hold the cables adjacent and parallel to each other. To reduce wind load, the cables are run up a tower in a 2 x 6 cable arrangement with space between the cables. Consequently, the maximum wind load is when the 2 rows of 6 cables are facing the wind with an effective area of 0.234 square meters per meter of height, 7 m² for the full 30m height.

The IEC 721-3-4 standard indicates a peak wind burst of 50 m/sec (180 km/hour) be considered; corresponding to the 3-second gust wind speed measured at 33ft above ground. [IEC72134]

The EIA/TIA-222-G standard [TIA222G] prescribes tables and equations for calculating the wind load as a function of height above the ground, so that the relative torque and twist on a mast can be evaluated. Assuming the default values of Topographic and Exposure categories corresponding to a flat field, the force on the cable versus 3 RRHs are Evaluated knowing that the wind velocity varies with the height and so the force is shown for every 1-meter section of cable.

** Civil and structural engineers make a distinction between a self supporting tower such as monopole while a mast uses guys or stays anchored into the ground for lateral support. Masts require an extended area surrounding them to accommodate the stay blocks. Towers are more commonly used in cities where land is in short supply.
The weight and moment (torque) resulting from this wind load integrated over the 30 meters of mast height are tabulated below:

<table>
<thead>
<tr>
<th></th>
<th>Twelve 1-1/4” LCFS114 Coax Cables For 4 branches/sector</th>
<th>6 Typical 2xpol Antennas</th>
<th>3 Typical Remote Radio Heads</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight</strong></td>
<td>330 kg</td>
<td>2x3x 15 kg = 90 kg</td>
<td>3x 17 kg = 51 kg</td>
</tr>
<tr>
<td><strong>Moment</strong></td>
<td>136 kNm</td>
<td>120 to 170 kNm</td>
<td>15 to 22 kNm</td>
</tr>
</tbody>
</table>

The representative antenna had an area of 0.48 m² and the Remote Radio Head (RRH) was exemplified with an area of 0.118 to 0.18 m². The moment is generally proportional to the area and to the square of the wind velocity. Keep in mind, too, that 2 branches per sector would amount to half the weight and as half the moment.

In addition, ice can accumulate on the cables and hardware, doubling the weight and adding to the effective area. In Table C.1 of the TIA-222-G standard, the impact of two different thicknesses of ice is prescribed for a 9-antenna configuration along with nine 1-5/8” cables configuration. This is a composite of all the antennas and cables together. (Note that the cables here are larger than the earlier example.)

<table>
<thead>
<tr>
<th></th>
<th>No Ice</th>
<th>ICE Thickness ≤ 0.5”</th>
<th>ICE 0.5” ≤ Thickness ≤ 1.5”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eff. Area</strong></td>
<td>6.5 m²</td>
<td>7.9 m²</td>
<td>10.2 m²</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>337 kg</td>
<td>337 kg</td>
<td>693 kg</td>
</tr>
<tr>
<td><strong>Scaled 6/9</strong></td>
<td>4.3 m²</td>
<td>5.3 m²</td>
<td>6.8 m²</td>
</tr>
<tr>
<td><strong>Moment</strong></td>
<td>182 kNm</td>
<td>222 kNm</td>
<td>285 kNm</td>
</tr>
</tbody>
</table>

The important comparison is that remote radio heads have less than 1/13th the weight and 1/6th to 1/9th the moment in high wind bursts. Icing and larger cables such as 1-5/8” make the comparison even more strikingly in favor of RRHs.

Both self-supporting and guyed masts are susceptible to ice and wind, but of course monopoles with cables inside the single hollow tube, shield the cables from icing and wind, but in monopoles, access to the cables is more difficult and constrained by size limits as all must fit through access holes such as those in the following photo in Figure 72.
In those cases where the lease agreements on the mast charge explicitly by static weight or wind load, the RRHs have a clear advantage, but the physical size of the RRH (though smaller than typical antennas) is occasionally an issue. On the other hand, maintenance and upgrades to an RRH can also present some difficulties due to the required tower climb. Therefore, making the RRHs robust and “future proof” with versatile software is a priority.

Moreover, when placing an RRH next to the antenna, the 2.5 to 3.5 dB of cable loss is reduced to less than 0.5dB, which can be used to either increase the transmitted power by 3 dB (doubling the power) or it can be used to reduce the power requirements on the amplifier, thus reducing the power consumption of the base station. When multiple carriers can be configured within the operating bandwidth of the RRH, the reduced RF losses can potentially permit about twice as many carriers at their full power.

While Remote Radio Heads (RRH) can be placed either near the antennas or on the ground with traditional cables running the distance to the antennas, the most appropriate configuration is unclear. Active equipment such as RRHs and Tower Mounted Antennas require “tower climbs” to repair or replace and requires that other sectors be turned down when field service engineers are working nearby. Upgrades to add additional power amplification or bandwidth beyond that originally provided by the RRH may require tower climbs to upgrade services, and some lease agreements require renegotiation when equipment of a different size/weight/appearance is installed.
Now available are armored cables and remote fiber feeders (RFF), combining the fiber and power elements in a single construction. A typical cable is shown in Figure 73. The cable consists of two fiber cable subunits each containing either 2, 4, or 6 tightly bundled fibers, which can be either single-mode or multimode. These are stranded around a central strength member along with three power conductors (positive, negative, ground). Around this stranded core is a water-blocking tape, ripcord, outer shield/armor, and the outer jacket. The conductor sizes are either 8 AWG or 10 AWG, depending on the power requirements of the Remote Radio Head Units, and the outer jacket can be either outdoor grade black polyethylene, for tower and monopole installations, or a low-smoke zero halogen compound for building installations.

These cables are typically installed one per sector between the main unit and the remote radio heads. Other configurations are possible, however, depending on the power consumption of the remote units and the associated voltage drop across the remote feeder. For example, a single cable might feed a remote unit at the top of a tower, which contains the radios for all three sectors. These would then connect to the antennas with regular coaxial cables.

Multiple fibers allow for flexibility, redundancy, and future-proofing of installations. Any or all of the fibers in one or both fiber subunits can be terminated with appropriate fiber connectors. Alternatively, the appropriate fiber and copper “break-outs” can be made and some fibers left to be terminated at some later date.
These cables, being a stranded construction, also allow the possibility of including additional elements such as an RET control cable, or an alarm cable, in custom designs.

6.6.2 ASSEMBLIES

Because the sizes are so small, correct termination of fiber optic cables requires more specialized tools and equipment and a higher skill level than does termination of coaxial cables. For this reason, fiber cables used with remote radio heads up to now have usually been pre-terminated assemblies. It is expected that the same will be true for the remote fiber feeders, at least for initial deployments. However, as this technology becomes more widespread there will likely be a requirement for field termination of fiber cables.

A typical breakout and termination scheme is shown in Figure 74. The outer shield and jacket are stripped back to the required lengths (say 0.5m at the RRH end and 1m at the main unit end) to expose the power conductors and one or both fiber subunits. The power conductors can be enclosed in heat-shrink or other tube material, and the main breakouts are sealed with epoxy and heat-shrink, which provides mechanical support and water blocking. The tightly-bundled fibers are individually broken out from the subunit cable a few inches from the ends, and terminated with suitable connectors per the equipment interfaces. Dual LC connectors seem to be the most commonly used currently.

Figure 74 — Breakout and termination scheme.
6.6.3 LIGHTNING PROTECTION

The outer shield on the Remote Fiber Feeder (RFF) cable provides basic support and mechanical protection, but also acts as a lightning shield. Power cables for outdoor installations often require electromagnetic shielding outside the conductors to reduce the induced transients on the conductors and minimize the possibility of damage to the electronic equipment, even though this may include integral or added surge suppression. The shields on the RFF feeders will withstand simulated strike currents in excess of 100kA with no damage to the cables. This is also a typical value for coaxial cables.

6.6.4 ACCESSORIES

Hoisting grips, hangers, and ground straps are available for the remote fiber feeder cables, and continue to be developed. Typical accessories are shown in Figure 75. These are similar to, and in some cases identical to, standard accessories for coaxial cables with which the installation community is familiar.
6.6.5 ADVANTAGES OF REMOTE FIBER FEEDERS

There are a number of advantages in using the combined fiber/copper remote fiber feeders, compared with the separate fiber and copper cables used up to now.

- Lower total material and installation costs. No conduit required.
- Ease of handling. One cable per sector. Ease of routing.
- Environmentally and mechanically protected.
- Reduced tower loading.
- Reduced tower real estate cost.
- Standard coaxial accessories.

6.7 CO-SITING OF MULTIPLE BASE STATIONS AND TECHNOLOGIES

6.7.1 SEPARATE FEEDERS FOR EACH SYSTEM

In an ideal world, each base station and air interface technology deployed on a cell site would have its own feeders and antennas. This would have several benefits:

- Individual optimization of antenna pattern, azimuth direction, and down tilt for each service.
- Minimum RF path loss and mismatch.
- Reduced concerns for interference and intermodulation between systems.
- Maintenance work on one system need not impact other services.

However, a number of constraints influence the site architecture and reduce the system designer’s options. In most situations, factors that must be considered include:

- Zoning restrictions on the quantity and design of antennas and other equipment.
- Limits on weight and wind loading of feeders and tower mounted equipment.
- Cost savings opportunities on capital expenditures, lease costs, and installation labor.
- Time to market requirements for rollout of new services.

A variety of co-siting solutions have been developed to address these constraints while enabling efficient operation of multiple technologies in a shared architecture. Today, these solutions are widely used within major carriers’ networks and competing operators have also joined together to reap the benefits of sharing site equipment.
6.7.2 SHARED FEEDERS—FREQUENCY MULTIPLEXING

Feeder cables are generally suitable for any frequency band and air interface technology and can therefore easily be shared. By combining services at the foot of the tower and again separating them just below the antennas, the benefit of individual antenna optimization is retained while reducing the number of feeders. Existing feeders can be used for additional frequency bands, helping accelerate rollout of new services.

Two or more frequency bands are combined or separated using Crossband Couplers. According to the number of paths combined, they are also known as Diplexers, Triplexers, etc. When the frequency separation between the bands combined is relatively wide, such as between 700-1000 MHz, 1700-2200 MHz, and/or 2400-2700 MHz, crossband couplers can be compact, low cost devices while introducing almost negligible loss and mismatch. When combining more closely spaced bands, for example a 700 MHz band coupler with another in the 850 MHz range, the components need to become somewhat larger and more complex in order to maintain acceptable performance.
6.7.3 SHARED ANTENNAS

Where individual antennas for each band and service cannot be installed, multiport and multiband antennas are used. This typically restricts the azimuth angle to be the same for all bands while beam tilt can be set independently for each antenna port or pair of ports. Crossband couplers or dual band TMAs are most often used to separate the bands below the antenna. However, multiband antennas (mainly dual band) with built in crossband couplers are also available on the market. These provide a very clean installation but with the disadvantage of not being able to support a TMA on one of the frequency bands.
Using broadband antennas specified for, e.g., 1700-2200 MHz, more than one band and service can be combined on a feeder and connected to a single antenna port. Antenna selection and adjustment may then involve a compromise that is acceptable, albeit less than optimal, for each service sharing the antenna. Technologies are available that allow individual beam steering but they come at additional cost and complexity.

6.7.4 SHARED FEEDERS AND ANTENNAS — SAME BAND COMBINING

When two or more services or operators share the same license band, regular crossband couplers cannot be used. In this situation, other solutions are available as described below. Same band combining is also often used with a single service to combine base station ports or cabinets when the channel count exceeds the capacity of a single unit. In Frequency Division Duplex (FDD) wireless systems, same band combining always involves distributing the uplink (RX) signals from shared antennas to multiple receivers and may also include combination of multiple base station transmitters to an antenna for the downlink (TX).
6.7.5 HYBRID COMBINING

Hybrid combiners provide a low cost method to simultaneously combine TX signals and divide RX signals. The main disadvantage is the high loss incurred in both directions, which increases steeply with the number of ports combined. When used with typical TX power levels, there is significant heat dissipation that must be managed. Therefore, this solution has limited popularity in cell site situations and is rarely used to combine more than two ports. It is more widely deployed for in-building coverage and similar applications.

6.7.6 LOW LOSS COMBINER—MULTIPLEXER

The Low Loss Combiner (LLC) is an alternate method to combine base station transmitters. Insertion loss in the LLC is significantly lower than in a hybrid combiner and it is less expensive compared to power amplifiers. On the downside, the LLC places constraints on the frequency ranges available to each system being combined.

Like a crossband coupler, an LLC is a filter multiplexer. While the former combines frequency bands spaced apart fairly widely, the frequency ranges combined in an LLC are all in the same band, leading to very small gaps—guard bands—between the ranges.
In some applications, guard band spectrum must be left unused and in order to minimize waste, the LLC is required to accommodate the smallest guard band possible without compromising insertion loss or distorting the signals. Such requirements lead to designs of increased size and cost. In other cases, the guard band spectrum can be reused on a second feeder and antenna. Thus, the LLC specifications may be relaxed and more economical design options can be chosen.

The LLC apportions a part of spectrum to each system. Future growth and de-growth, and other spectrum redistributions will require reconfiguration, retuning, or replacement of the LLC. Remotely tunable equipment has been introduced to partially alleviate these restrictions.

While LLCs are primarily employed for downlink combining, a corresponding filter multiplexer can also serve to distribute uplink signals. It holds the advantage of not requiring supply power but is overall less popular than the receiver multicoupler method described below.

Some base stations on the market also have the ability to distribute a part of the signal from each RX branch after the receiver LNA. This makes it possible to design a smaller combiner unit without the need for other compensation of uplink combiner loss.

6.7.7 SINGLE CARRIER POWER AMPLIFIERS (SCPA)

Preceding a hybrid combiner, an SCPA compensates for the combining loss. Being a non-linear amplifier, an SCPA can itself be quite energy efficient but is suitable only for GSM and some similar technologies. Overall efficiency is reduced by hybrid losses and need for heat management. The relatively simple amplifier circuits moderate unit cost.

6.7.8 MULTI-CARRIER POWER AMPLIFIER (MCPA)

The MCPA is a high power linear amplifier capable of combining and amplifying multiple RF carriers into a single output. An MCPA usually includes one or more amplifier “bricks” that work in parallel to provide the needed output power. Input circuits can be expanded to accommodate from two up to eight or more carriers.
ports. Integrated duplexers route the uplink signals around the MCPA and RX amplification/distribution can be incorporated.

Advantages of the MCPA include the ability to boost downlink power for increased coverage and/or capacity as well as complete frequency agility, placing no restrictions on what channel frequencies are used within a license band. They can be used with any air interface technology, even combining multiple technologies. On the other hand, large MCPA systems can entail a significant investment and they are not very energy efficient.

Modern base stations, such as for UMTS and LTE, mostly include MCPAs as an integrated part of the Radio Unit. Here the power output of the PA is closely monitored and adapted to current traffic situations as part of the overall base station performance management. As an external MCPA will be connected outside of this monitor and control loop, it is less suitable for co-siting with this type of base stations.

6.7.9 RECEIVER MULTICOUPLER

A Receiver Multicoupler (RXMC) distributes uplink signals from shared antennas to multiple receivers. A power splitter divides the input signal to a number of output ports. Preceding the power splitter, a Low Noise Amplifier (LNA) compensates the splitting loss, preserving uplink sensitivity. At the input to the LNA, a preselector filter may be integrated with the RXMC or exist as a part of other site equipment.
Characteristically, the RXMC distributes the full RX frequency band to all outputs. The net gain or loss is often the same for all outputs but unequal division is also a design option where the RXMC serves receivers with differing input level requirements or where the signal will be further divided before reaching the receivers.

For applications with few outputs – usually just two – a power splitter without LNA is sometimes used.

### 6.7.10 INTEGRATED DEVICES — SAME BAND COMBINER

The generic term Same Band Combiner (SBC) refers to a device that passes uplink and downlink signals, incorporating some combination of same band transmit combining and/or receive signal distribution using any of the methods described above, excluding power amplifiers. The configurations vary with application.
Figure 90 – Antenna sharing using TX/RX quadriplexer.

Figure 91 – RX distribution to simplex BTS using duplexers and RXMC.

Figure 92 – Antenna sharing using integrated SBC.

Figure 93 – Dual RXMC with eight outputs per channel.
6.7.11 TOWER MOUNTED AMPLIFIERS

A Tower Mounted Amplifier (TMA) is installed near the receiving antenna. Its purpose is to boost the uplink signal before it is degraded by losses in the RF path to the receiver, thereby improving signal quality and base station sensitivity.

6.7.12 BENEFITS OF TOWER MOUNTED AMPLIFIERS

TMAs provide benefits for all air interface technologies. Their fundamental effect on the uplink is an improvement in carrier-to-noise ratio (C/N). Improvement of around 5-6 dB is typical but the amount varies according to RF path configuration. This additional link budget margin can be utilized to improve various network performance parameters such as:

- Coverage – in terms of cell radius as well as weak spots and indoor locations
- Accessibility – failed access attempts
- Retainability – dropped call rates
- Co-channel interference – call capacity in spread spectrum systems
- Data throughput – enabling higher order modulations
- Average handset output power – battery drain

Adjusting base station settings, the operator can optimize between the available benefits to obtain the best overall Quality of Service (QoS).
6.7.13 CONFIGURATIONS

The key element in the TMA is the Low Noise Amplifier (LNA). It is always preceded by a preselector filter. Today's TMAs are universally of the dual duplex type, which allows use in duplexed feeders. Thus, two additional filters are included to pass the downlink and isolate the LNA. Most often, the filter bandwidths cover a full license band but other variants occur, including filters with additional out-of-band rejection to improve BTS interference immunity.

A TMA can be a single band device as above. Increasingly, single-band TMAs are provided as integrated pairs in dual, or twin, assemblies in order to reduce cost, weight, and the number of devices on the tower.

Dual band TMAs combine two single band TMAs in one device. There may be a separate RF path for each band or they may be diplexed into a single path at the BTS port and/or ANT port. Diplexers can also be integrated with single band TMAs creating units with non-amplified RF paths often referred to as bypass or pass-through configurations.

Deployment of additional license bands is leading to further consolidation into TMAs supporting more than two RF paths and frequency bands, again driven by efforts to avoid additional units of tower mounted equipment.

6.7.14 ENHANCED FEATURES — AISG

The Antenna Interface Standards Group (AISG) is an organization whose membership includes the majority of leading wireless equipment manufacturers and many major wireless operators. Since its foundation in 2001, AISG has driven the development of a protocol for communication between base stations and tower top equipment, including antennas, TMAs, and other devices. The universally adopted AISG protocol facilitates control and monitoring of functions such as antenna down tilt and TMA alarms.

Early implementations utilized separate cables for the connection between base and tower. More recently, a system is increasingly favored where the signals are borne by a 2 MHz carrier on one or more feeder cables. The components in the RF path must then be designed for compatibility with AISG communication whether they process the signals or simply pass the low frequency carrier. For example, crossband couplers may have DC and control signal bypass or block on one or more of their branches.

The AISG protocol provides a platform for implementation of advanced features in tower top equipment, allowing better performance optimization and diagnostics while ensuring interoperability between any devices supporting the standard. Adding remote connectivity to the AISG system will also reduce the frequency of site visits, having beneficial impact on the operating budget.
Figure 95 – Single band TMA.

Figure 96 – Twin single band TMA with AISG support.

Figure 97 – TMA with integrated diplexer.

Figure 98 – Dual band TMA with AISG support.

Figure 99 – Diplexed dual band TMA with AISG support.

Figure 100—Dual diplexed dual band TMA with AISG.

Figure 101 – Diplexed dual band TMA with pass-through and AISG.
6.8 INDOOR DISTRIBUTED ANTENNA SYSTEM — MIMO COVERAGE

In many countries, more than 70% of the traffic on cellular networks originates from or terminates inside buildings. Driven by an increasing demand for mobile data services, the iPhone effect, this number is expected to rise even higher within the next years.\(^{47}\) When rolling out new systems addressing high-speed data needs, e.g., LTE or HSPA+, a cost effective solution is explored by extending the outdoor macro coverage to inside. In order to reduce the building penetration path loss a relay can be used to amplify and forward (A&F) or decode and forward operation (D&F) the signal. The benefits of a D&F relay on the achievable LTE downlink indoor coverage extension has been demonstrated in “Relaying in Long Term Evolution: Indoor Full Frequency Reuse.”\(^{48}\) Implementing the D&F relay, however, adds complexity to the system and decreases overall air-interface capacity due to the in-band backhauling.

In the A&F mode, the relay terminal simply amplifies and retransmits the signal received from the source terminal. Figure 102 compares the results measured at the Heinrich Hertz Institute in Berlin by applying both relay technologies.

![Graphical representation of the in-building coverage measured with: a) a D&F relay where 50% of the link capacity is allocated for in-band backhauling,\(^{47}\) and b) an A&F optical DAS with an interleaved antenna arrangement.\(^{49}\)](image)

In order to obtain the best cost-to-coverage solution, several antenna configurations have been investigated.\(^{49}\) Due to the fact that an interleaved distributed antenna arrangement can be set-up by re-cabling of an existing single antenna 2G or 3G distribution system this solution turned out to be the most advantageous. At a minimal upgrade cost, it provides exceptional data rates and the LTE pre-coding supports the transmission of two separate spatial data streams at two different antennas. It is therefore possible to fully exploit the rich scattering that exists in most in-building environments.
In addition to the in-building coverage test, it could be shown that a MIMO coded signal can be transmitted without any performance degradation in good LOS conditions. A fact which is good to remember when the distribution system has to be fed by picking up the signal off air.

In the face of all the enthusiasm about the possibility to boost the in-building data rate by deploying MIMO technologies, it has to be mentioned that a sufficient Signal-to-Interference-and-Noise Ratio (SINR) is the price which has to be paid. As shown in Figure 103a) a minimum SINR of 26 dB is required to enhance the capacity of a Single Input Single Output (SISO) system by 50%. To justify the cost for a second RF infrastructure it is assumed that a data rate enhancement of 70 … 80%, i.e., a SINR of 40 … 50 dB is required. For these capacity calculations, a measured average channel condition number\(^5\) of 14 dB, valid for a small/office in-door environment, has been assumed. To estimate the required RF power per antenna at 2.6 GHz in a typical indoor environment the scenario B3 (hotspot large indoor hall) based on the WINNER\(^5\) propagation model is shown in Figure 103. Hence depending on the number and thickness of the walls to be taken into account, a similar path loss can be expected for scenario A1 (indoor office / residential). For simplicity, let us assume a minimum UE receiver’s sensitivity of -100 dBm in a 20 MHz bandwidth. Taking into account 60 … 80 dB path loss, a RF power level of -40 … -20 dBm at the receiver is required. Targeting for a minimum data rate enhancement of 70%, this results in 0 … +20 dBm radiated power at each antenna per carrier bandwidth. Alternatively to increasing the RF power the numbers of antennas can be increased and thus the spacing in between reduced. It also should be mentioned that the situation can be improved by operating at lower frequencies, e.g., at 700 … 800 MHz where the path loss is expected to be 10 … 15 dB lower.

Figure 103 – Important graphs for MIMO link budget considerations: a) data rate enhancement MIMO vs. SISO as a function of SINR, and b) typical indoor path loss graphics @ 2.6 GHz (WINNER II channel model).

Another point of interest, especially for in-building MIMO distribution systems, is the minimum spacing in-between the antenna dipoles to ensure the maximum data rate enhancement. The amount of additional transport capacity, provided by different spatial MIMO streams, is directly linked to the de-correlation of these streams. Since the correlation between two antenna dipoles is increasing the closer they come it might be expected that the data rate enhancement may drop accordingly. However it has been shown that local scatterers, in the near vicinity of the antenna elements significantly decrease this effect.\(^5\)\(^2\) It turned out that not the antenna spacing but the angular spreading of the incident waves is the determining factor for the antenna de-correlation. Especially in rich scattering indoor environments it has
been proven by experiment that a spacing of $\lambda/2$ is already enough to guarantee a reasonable data rate enhancement.\textsuperscript{53}

In low scattering indoor environments, e.g., large hallways or conference rooms, a low angular spreading has to be expected. This is a phenomenon, which is well known from outdoor, above rooftop, antenna installation.\textsuperscript{54} Unless large antenna spacing, e.g., interleaved indoor antenna arrangements (as described in the previous paragraph) can be used, it is assumed that cross-polarized antennas are advantageous for indoor installations as well. Results show that increasing the de-correlation by polarization performs better than increasing the antenna spacing in strong line of sight (LOS) scenarios. In non line of sight (NLOS) scenarios, the results are of the same order.\textsuperscript{55}

7 TERMINAL ANTENNAS

7.1 PROSPECTS AND CHARACTERISTICS OF MULTIPLE ANTENNAS IN TERMINALS

In a previous 3G Americas white paper on MIMO and smart antenna technology, many of the problems faced by user equipment (UE) vendors were discussed. The problems range from issues of antenna correlation and coupling, the challenges of designing and manufacturing small-sized UE devices, multi-band support and user effects. General knowledge of the solutions to these problems is fairly well known. For instance, as antennas are separated, they tend to have less correlation and coupling. It is very hard to generate specific data on the impact of real antennas on smart antenna systems because the implementations will be diverse across device size and designer preferences (antenna type, polarization and/or pattern diversity). Accumulation of this data will have to be done with the large-scale deployment with many devices. Carriers are probably in the best position to catalogue this information given the large number of deployed devices.

In order to provide insight into the effects that actual deployment of UE antennas will have on smart phones sized devices, we provide an analysis that attempts to address the two most important parameters in wireless communication systems: link budget and capacity impact. One of the first things that a system designer is going to want to know is the antenna gain of the UE, given that there are two antennas now required for LTE. In other words, how much additional gain can be expected with the use of both antennas relative to a single antenna. Given that techniques such as pattern and polarization diversity can be employed to help de-correlate arriving signal paths, the question arises as to what the impact of the antenna patterns is going to be.

To investigate the link budget impact, we have done a study using an approach similar to that described in an IEEE paper.\textsuperscript{56} This study was done with antenna types that are likely to be used within a typical smart phone dimension for use in LTE MIMO mobile systems. The objective of the study was to try to characterize the relative performance improvement in the link budget that would be realized in a MIMO-based LTE system from the use of two receive antennas relative to the single antenna systems most commonly used in current UEs.

This study was set up with the following two scenarios.
1. A phone placed in between a phantom head on one side and a phantom hand placed on the opposite side of a phone. This provides a realistic situation in which to examine antenna performance for mobile devices since this is a very common usage pattern of users. This scenario provides fairly large absorption and shielding losses because the antenna is shielded by both the head and hand. However, even though the mutual coupling between the antennas tends to increase the magnitude and phase of the radiation pattern, changes such that the antennas tend to be less correlated than in a free space scenario. This de-correlation tends to overcome the absorption loss and increases the performance relative to two antennas in free space. This scenario is illustrated in Figure 104 and is referred to as the Voice Mode.

2. A phone placed in front of the body held with the hands. This is a common usage scenario for texting or web surfing. This scenario is illustrated in Figure 104 and is referred to as the Data Mode.

![Voice Mode and Data Mode](image)

Figure 104 – Position of the handheld device for the two scenarios.

In our study, we used several different head and hand models and averaged the results. This probably accounts for most of the differences in performance between our study and reference. However, the exact form factor, antenna location, antenna type, and orientation are also factors that will yield different performance values. The study was carried out via software simulations with the GEMS and FEKO software tools as well as anechoic chamber measurements, which confirmed the simulations given the close agreement between the two sets of data. Table 6 shows the results for the Voice Mode. Table 7 shows the results for the Data Mode. The “Improvement” column is the data that was simulated and measured in this study. The “Improvement from” column is the data found referenced in, “Actual Diversity Performance of a Multiband Diversity Antenna with Hand and Head Effects.” Note that the simulated and measured results include diversity gain, and are relevant to control channel reception in a UE.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Improvement (dB)</th>
<th>Improvement [4] (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>2 to 5</td>
<td>--</td>
</tr>
<tr>
<td>850</td>
<td>2 to 5</td>
<td>5-6</td>
</tr>
<tr>
<td>950</td>
<td>3 to 6</td>
<td>5 to 6</td>
</tr>
<tr>
<td>2100</td>
<td>6 to 9</td>
<td>8 to 10</td>
</tr>
</tbody>
</table>

Table 6—Link budget receive performance improvement due to two receive antennas over one receive antenna on a handheld placed between a phantom head and hand.
Table 7 – Link budget receive performance improvement due to two receive antennas over one receive antenna on a handheld placed in front of user in a typical data usage fashion.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Improvement (dB)</th>
<th>Improvement (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>4 to 6</td>
<td>--</td>
</tr>
<tr>
<td>850</td>
<td>5 to 7</td>
<td>8 to 10</td>
</tr>
<tr>
<td>950</td>
<td>5 to 8</td>
<td>8 to 10</td>
</tr>
<tr>
<td>2100</td>
<td>7 to 10</td>
<td>8 to 10</td>
</tr>
<tr>
<td>2600</td>
<td>7 to 10</td>
<td>--</td>
</tr>
</tbody>
</table>

To get an indication of the possible loss of capacity that may occur when using two realistic antennas, we calculate the maximum capacity possible under ideal conditions using uncorrelated isotropic antennas and compare those results to that of a design that would contain realistic antennas. The realistic design for a smart phone will utilize the well-known inverted-F antenna (IFA) technology. The design is cross-polarized and we look at two frequencies: 2.6 GHz (190 MHz bandwidth) and 780 MHz (40 MHz bandwidth). These are two prominent LTE frequency bands. In this study, we do not take into account the effects of the head and hands.

To measure the maximum capacity we use Shannon’s generalized capacity equation:

\[ C = \log_2 \det(I_N + \frac{\rho HH^H}{N_T}) \]

Where \( \rho \) is the average signal-to-noise ratio, \( H \) is the channel at each subcarrier, \( I_N \) is the identity matrix and \( N_T \) is the number of transmit antennas. With this equation, if we can impose the effects of the antennas on the channel matrix, we can generate the upper limit of the capacity of a single MIMO radio link with equal power transmitted per layer.

This can be done by importing the antenna patterns into the spatial channel model (SCM\textsuperscript{59} that is used extensively by 3GPP) and generating \( H \) with their effects. The parameters for 780 MHz that are plugged into the model are shown in Table 8. As you can see we assume that the base station antenna configuration can be modeled as two dipoles separated by 20 wavelengths (i.e., they are uncorrelated). Figure 105 and Figure 106 exemplify transmit and receive antenna configurations that contain angle spread and orientation.

Table 8 – SCM parameters for 2x2 780 MHz antenna system.

<table>
<thead>
<tr>
<th>SCM Urban Macrocell Parameters</th>
<th>BS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuth Angle Spread</td>
<td>8 deg</td>
<td>68 deg</td>
</tr>
<tr>
<td>Azimuth Array Orientation</td>
<td>0 deg</td>
<td>0 to 180 deg</td>
</tr>
<tr>
<td>Elevation Angles</td>
<td>0 deg</td>
<td>-90 to 90 deg</td>
</tr>
</tbody>
</table>
In an effort to isolate the effect of realistic antennas, we compute the capacity at a given average SNR at the antenna input by averaging the Shannon capacity over multiple independently faded channel realizations. By further accounting for the angular power distributions in azimuth and elevation, we can compare the results of a realistic set of antennas with the results of doing the same with an isotropic antenna and gain insight into the capacity impact of more realistic antennas. Figure 107 shows the result of this for both 2.6 GHz and 780 MHz antennas. Note that the orientations are averaged to provide one resulting curve. UE is moving at the speed of 10 m/s. Looking at the 10 dB SNR mark, it can be seen that an extra dB of SNR for the UE with an IFA antenna pair is needed to achieve the capacity upper limit that you would get with an isotropic antenna pair. At 10 dB SNR, there is a loss of 0.5 bps/Hz or 9.5% for the UE with 2.6 GHz IFA antenna pair. For 780 MHz antenna pair, there is a loss of 1.8 bps/Hz or 35% at 10 dB. Note that in all the simulations, the effect of antenna efficiency is incorporated.
In conclusion, we have examined the effects of realistic antennas in a smart-phone form factor on link budget performance and maximum link capacity. We have noted from a study performed for this document that there will be a link budget improvement of 2 dB at lower frequencies to around 6 dB at some of the higher LTE frequency bands. Others have shown greater gains than that. On the other hand, we see that realistic antenna designs in realistic environments will see a loss of maximum capacity potential of over 30%.

### 7.2 UE PERFORMANCE AT 750 MHZ WITH MIMO

In order to obtain insight into the MIMO performance at lower frequencies, a number of studies, simulations, and field trials have been carried out on four realistic dual-antenna devices. First, the antenna characteristics at link level are analyzed followed by system simulations. Finally, the devices are used in a field trial to assess the performance in a cellular network.

A set of realistic dual-antenna phones\(^{61}\) has been manufactured, and simulations and measurements have been performed at both antenna level and system level to assess the performance at 750 MHz. Four different dual-antenna UE devices are used. Two feature-sized phones were designed with the outer dimensions 115 x 65 x 12 mm\(^3\) (0.29\(\lambda\) x 0.16\(\lambda\) x 0.03\(\lambda\) at 750 MHz). The first Feature Phone (FPA) has a monopole main antenna located at the bottom edge of the device, while an equally aligned second monopole antenna is placed at the top edge. The second Feature-Phone (FPB) has a notch orthogonally placed along the side edge as the second antenna. Another set of two slightly larger phones has the outer dimensions of a smart-phone, e.g. 150 x 73 x 22 mm\(^3\) (0.37\(\lambda\) x 0.18\(\lambda\) x 0.06\(\lambda\) at 750 MHz). The
main monopole antenna is located at the top edge while a Planar Inverted-F Antenna (PIFA) is orthogonally placed at the lower edge in one device, Smart Phone (SP1). The other Smart-Phone (SP2) has two co-located loop antennas positioned at the bottom edge.

The dual-antenna realizations (FPA, FPB, SP1, and SP2), such as radiating element types, antenna orientations, and antenna positioning, are designed on purpose for low, mid, and high antenna branch signal correlation in order to evaluate impact on performance. In particular, SP2 has a very high antenna branch signal correlation in order to serve as a reference case with extremely low probability of multi-layer transmission.

Free space embedded radiation patterns of the two antennas in each device have been recorded. The received antenna branch signals are then calculated by combining the embedded far field radiation patterns with a spectrum of complex incident rays as illustrated in Figures 104 and 105. The Shannon downlink capacities of the 2 x 2 MIMO antenna systems are calculated for each device assuming water filling at the transmit side. The mean capacity at a signal-to-noise ratio (SNR) level of 20 dB is plotted in Figure 108 as a function of the antenna mean efficiency, where the efficiency per antenna port is defined as incident over radiated power, with the other port terminated with a matched load. The small dots correspond to a dipole case simulation study for two dipole antennas with a large range of efficiency and antenna branch signal correlation values. The solid lines are theoretical curves for various signal correlation values. A spherical uniform spectrum of the incident field is assumed. As seen, efficiency is a critical antenna parameter while complex correlation values below 0.5 have a minor impact on the Shannon capacity.

![Figure 108 – Mean 2 x 2 MIMO Shannon downlink capacity at 20 dB SNR of dual-antenna devices in a uniform 3D environment as a function of the antenna efficiency and correlation.](image)

Downlink system simulations have been performed on the devices with a multi-cell LTE radio network simulator, which includes the 3GPP Spatial Channel Model (SCM) and models of, e.g., adaptive coding and modulation, device mobility, and delays in channel quality reports. The performance is assessed using system and user throughput. The 3GPP cases 1 and 3 are studied with the SCM environment. Table 9 shows system, cell-edge (5%), and peak (95%) throughput for the four antenna devices relative to two ideal dipoles with no loss and zero correlation. All throughput values are normalized so that 100% corresponds to the throughput obtained when using the ideal reference dipoles. The base stations are assumed to have dual-polarized ±45° antennas. It is clear that devices with well-designed antennas
achieve MIMO performance on par with the ideal reference case, particularly in an urban macro scenario with high inter-cell interference (3GPP case 1).

Table 9 – 2 x 2 MIMO downlink throughput of devices relative to two ideal dipoles (in percent).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FPA</th>
<th>FPB</th>
<th>SP1</th>
<th>SP2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3GPP case 1,</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>high load</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>88%</td>
<td>96%</td>
<td>99%</td>
<td>71%</td>
</tr>
<tr>
<td>Cell-edge</td>
<td>78%</td>
<td>93%</td>
<td>96%</td>
<td>67%</td>
</tr>
<tr>
<td>Peak</td>
<td>92%</td>
<td>97%</td>
<td>100%</td>
<td>72%</td>
</tr>
<tr>
<td><strong>3GPP case 3,</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>low load</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>75%</td>
<td>83%</td>
<td>90%</td>
<td>64%</td>
</tr>
<tr>
<td>Cell-edge</td>
<td>59%</td>
<td>67%</td>
<td>77%</td>
<td>50%</td>
</tr>
<tr>
<td>Peak</td>
<td>81%</td>
<td>90%</td>
<td>95%</td>
<td>55%</td>
</tr>
</tbody>
</table>

A field trial has also been performed to investigate how MIMO works in a cellular network at LTE band 13 (746 – 756 MHz in downlink). The purpose of the campaign was to test the four different dual-antenna UE designs in order to obtain qualitative results on their relative performance. In the trial, 2x2 MIMO in downlink was tested, i.e. two receive branches at the device and two transmit branches at the base station. This is the typical setup for today’s deployed LTE networks. The deployed base station antenna systems employed dual-polarized antennas. The network used was a pre-commercial LTE network.

The trials were performed in a radio environment as similar as possible to what handheld devices will experience in a live LTE network. In order to achieve this, different load conditions were created, hand dummies were used, and areas with different town architectures (urban and suburban) were used for the test campaign. Hence, results regarding the interaction of hands holding the device and vehicle components surrounding it were also obtained.

Three use modes were included in the trials: hands on roof, hands in van, and free space on roof. The hands on roof and hands in van use modes included hand dummies. The devices were placed in a two-hand data mode, Figure 103b. In the hands in van use mode, the devices and hands were placed to the right hand side of the driver’s seat; in the hands on roof use mode, they were placed on the roof of the van.

shows the mean throughput achieved over the measurement drives normalized by the roof-mounted reference dual (vertical and horizontal) dipole antenna measurements. In the measurement drives, three (SP1, FPA, and FPB) out of the four devices and the reference set-up performed similarly. These devices were able to select multi-stream transmission to a large extent while device SP2 in practice never selected multi-stream transmission.

Figure 110 illustrates the proportion of rank 2 (MIMO) selection made by the devices over the drive routes. The devices selected MIMO transmission frequently; in many measurement routes almost as often as the roof-mounted reference dual-antenna set-up. The reference was significantly better only when compared to the handheld data modes. This difference was not as evident in throughput; there was
a range of channel conditions where rank 2 and rank 1 transmission can be expected to perform almost similarly.

Figure 109 – Mean throughput normalized to reference antenna throughput for the four devices.

Figure 110 – Proportion of rank 2 (MIMO) selection for the four devices and the reference dual dipole set-up.
It is evident from the trial that MIMO performs very well with handheld devices also at lower carrier frequencies. However, MIMO performance will be very poor if the antenna system is not designed targeting low correlation properties. Device SP2 had much lower performance than the other devices and the dual dipole antenna reference set-up due to the design of SP2 giving intentionally high antenna branch signal correlation. This is shown in both its low ability to select rank 2 MIMO-transmission and in the throughput figures.

The trials also showed that the effect on MIMO performance with hands holding the device was relatively large with certain antenna designs. This further emphasizes the importance of a careful antenna design.

The effect of device placement inside the test vehicle was mainly loss of signal strength. Such loss may be very significant in a power limited scenario. The same applies to antenna efficiency. The majority of the tested cases were not mainly power limited rather interference limited, and hence the effect of the in-van placement on throughput was relatively small. However, note that the body style of the vehicle was probably an important aspect when characterizing the in-vehicle radio channel, hence results obtained may only be valid for the type used in the trials, i.e., a panel truck with no windows behind the in-van devices.

### 7.3 CURRENT STATUS OF TERMINAL ANTENNAS

Multiple antennas are currently found in the terminals of many wireless products, particularly PCs, data cards, and USB dongles. See for example, the products whose antennas are photographed below in Figure 111 through Figure 113 below.

Of course, terminals are not just handsets anymore. Mobile terminals such as the Kindle and iPad, not to mention laptops and notebooks that have integrated UT built in have a great deal of room for multiple antennas. Beyond the FM radio antenna, GPS receiver, WiFi and multiple band antennas, they also now support multiple antennas as well.
Figure 111 – Modern multi-band terminal antenna design with 3 feeds, courtesy of TDK
Figure 112 – Example antennas from representative handsets, illustrating manufacturing and design approaches.
Figure 113 – Photo of the Inside of the Amazon Kindle showing two antennas for PCS band use.

### DEFINITIONS AND ACRONYMNS

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
</table>

128

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<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Upper Sidelobe Level</td>
<td>Level of the 1st sidelobe on the upper half space of the elevation pattern relative to the main beam peak level.</td>
</tr>
<tr>
<td>3rd Order PIM (Passive Intermodulation)</td>
<td>3rd order intermod products using two 20W (2 x 43dBm) carriers; 3rd order product defined at frequencies of (F1 +/- 2<em>F2) and (F2 +/- 2</em>F1) falling within the receive band when transmit frequencies F1 and F2 are used as the input carriers. The output is typically specified to be -150dBc or better.</td>
</tr>
<tr>
<td>Integrated Antenna/Radio</td>
<td>Active Antenna – with power amplifier, LNA, filter and CPRI connection integrated into one radome. This is a special case of the more capable AAS antenna array insofar as it only controls the horizontal directions of the beams/MIMO parameters.</td>
</tr>
<tr>
<td>AAS</td>
<td>Active Antenna System – A two dimensionally controlled array of antenna elements, each with their own radio, power amplifier, filters and LNA so that beams or complex weights can be applied to the antenna array in both horizontal as well as vertical directions, suitable for “3D-beamforming.” This is a two dimensional extension of the simpler Integrated Antenna/Radio concept.</td>
</tr>
<tr>
<td>AISG</td>
<td>Antenna Interface Standards Group Specified interface control signals for RET and RAZ as well as power.</td>
</tr>
<tr>
<td>Azimuth Beampeak</td>
<td>Beam pointing angle (in Azimuth plane) defined using center of 3dB points; referenced to a mechanical boresight.</td>
</tr>
<tr>
<td>Azimuth Beamwidth</td>
<td>Typically stated as 3dB beamwidth (unless otherwise specified); Defined as the angular width of the azimuth (horizontal) pattern, including beam maximum, between points 3dB down from beam max level.</td>
</tr>
<tr>
<td>Azimuth Fan Range</td>
<td>Range of Azimuth Beamwidths achievable by the antenna device.</td>
</tr>
<tr>
<td>Azimuth Pan Range</td>
<td>Angular range of azimuth beampeaks through which the azimuth pattern will sweep MECHANICALLY via physical movement of the antenna device (usually defined as +/- X from boresight direction).</td>
</tr>
<tr>
<td>Azimuth Roll-off</td>
<td>Pattern level defined at the sector edge angles relative to mechanical boresight (adjusted for azimuth pan angle offset) where the sector is defined as follows:</td>
</tr>
<tr>
<td></td>
<td>* For a nominal Azimuth Beamwidth of 45deg or Narrower (i.e. 33/45), a 60deg sector is defined (-30/+30deg sector).</td>
</tr>
<tr>
<td></td>
<td>* For a nominal Azimuth Beamwidth Wider than 45deg (i.e. 65/85), a 120deg sector is defined (-60/+60deg sector).</td>
</tr>
<tr>
<td>Azimuth Scan Range</td>
<td>Angular range of azimuth beampeaks through which the azimuth pattern will sweep ELECTRICALLY with the antenna device fixed (usually defined as +/- X from boresight direction, azimuth counterpart to elevation beamtilt range).</td>
</tr>
<tr>
<td>Band-to-Band Squint</td>
<td>Measured as max angular deviation between overlay of AZ patterns for 2 ports in different frequency bands of a single or dual pol antenna - mechanical boresight required for a single port in a single band, all other ports/bands measured from same mechanical boresight.</td>
</tr>
<tr>
<td><strong>Band-to-Band Tracking</strong></td>
<td>Measured at max magnitude deviation over the defined sector (adjusted for azimuth pan angle offset) of AZ pattern overlay for 2 ports in different frequency bands of a single or dual pol antenna - mechanical boresight required for a single port in a single band, all other ports/bands measured from same mechanical boresight. The sector is defined as follows: * For a nominal Azimuth Beamwidth of 45deg or Narrower (i.e. 33/45), a 60deg sector is defined (-30/+30deg sector). * For a nominal Azimuth Beamwidth Wider than 45deg (i.e. 65/85), a 120deg sector is defined (-60/+60deg sector).</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Beam Tilt</strong></td>
<td>Defined using center of 3dB points; referenced to a mechanical boresight.</td>
</tr>
<tr>
<td><strong>Beam Tilt Range</strong></td>
<td>Defined as the range of angles - min-to-max - that the antenna will scan in the EL pattern.</td>
</tr>
<tr>
<td><strong>CLA Clustered Linear Array Antennas</strong></td>
<td>Family of clustered linear antenna configurations such as those resulting from forming clusters of closely spaced antenna elements while separating these clusters either by widely spacing them or by different polarizations.</td>
</tr>
<tr>
<td><strong>Connector Location</strong></td>
<td>Physical mounted location of antenna port connectors: Bottom, Back.</td>
</tr>
<tr>
<td><strong>Connector Type</strong></td>
<td>Type of Connector used on antenna port(s) Typically DIN 7/16.</td>
</tr>
<tr>
<td><strong>CPRI</strong></td>
<td>Common Public Radio Interface™ Specification of interface from base band unit to remote radio heads.</td>
</tr>
<tr>
<td><strong>DIV array antennas</strong></td>
<td>Family of diversity antenna configurations such as those resulting from all elements being widely spaced or separated by different polarizations.</td>
</tr>
<tr>
<td><strong>Elevation Beamwidth</strong></td>
<td>Typically stated as 3dB beamwidth (unless otherwise specified); Defined as the angular width of the elevation (vertical) pattern, including beam maximum, between points 3dB down from beam max level.</td>
</tr>
<tr>
<td><strong>Frequency Range</strong></td>
<td>Operating frequency band the antenna will perform to spec over.</td>
</tr>
<tr>
<td><strong>Front-to-Back Ratio (co-pol only)</strong></td>
<td>Pattern level discrimination measured at 180deg relative to azimuth beam pointing angle – &gt; determined using Co-pol Azimuth pattern only.</td>
</tr>
<tr>
<td><strong>Front-to-Back Ratio, Angular Region (total power)</strong></td>
<td>Pattern level discrimination measured over an angular back region defined as 180deg +/- 30deg relative to azimuth beam pointing angle – &gt; determined using Total Power Azimuth patterns (achieved via vector sum addition of co-pol &amp; x-pol patterns).</td>
</tr>
<tr>
<td><strong>Front-to-Back Ratio, Angular Region (co-polarized only)</strong></td>
<td>Pattern level discrimination measured over an angular back region defined as 180deg +/- 30deg relative to azimuth beam pointing angle – &gt; determined using Co-pol Azimuth patterns only.</td>
</tr>
<tr>
<td><strong>Front-to-Side Ratio</strong></td>
<td>Pattern level discrimination defined at +/-90deg relative to mechanical boresight (adjusted for azimuth pan angle offset) in the Azimuth co-pol pattern.</td>
</tr>
<tr>
<td><strong>Gain</strong></td>
<td>Measured antenna gain using a Swept Frequency Gain-by-Comparison method (std procedure) involving a Standard Gain Antenna with Published Absolute Gain.</td>
</tr>
<tr>
<td>Metric</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| H/V Tracking                               | Discrimination between H-pol & V-pol AZ pattern over the defined sector (adjusted for azimuth pan angle offset) of AZ pattern component cuts for x-pol antennas where the sector is defined as follows:  
* For a nominal Azimuth Beamwidth of 45° or narrower (i.e. 33/45), a 60° sector is defined (-30/+30° sector).  
* For a nominal Azimuth Beamwidth Wider than 45° (i.e. 65/85), a 120° sector is defined (-60/+60° sector). | dB    |
| Impedance                                  | 50 ohm system reference                                                                                                                                                                                 | ohms  |
| Maximum Upper Sidelobe Level               | Level of the maximum sidelobe on the upper half space of the elevation pattern from horizon to zenith relative to the main beam peak level.                                                              | dB    |
| Null Fill                                  | Defined as the depth of the 1st null in the lower half space of the elevation pattern relative to the main beam peak level - typically defined as the 1st lower null fill between the main lobe and 1st lower sidelobe. | dB    |
| ORI                                        | Open Radio Equipment Interface, an ETSI standards effort is a direct result of requirements work undertaken by the NGMN Alliance, in their OBRI (Open BBU RRH Interface) project. It extends the CPRI work to include Synchronization, L1, HDLC, Ethernet and vendor specific signaling. |       |
| Polarization                               | Definition of antenna port(s) polarization: +/- 45° Slant, Hor, Vert, Hor/Vert, LHCP, RHCP.                                                                                                            | degrees |
| Port-to-Port Isolation (In-band / Intra-band / Intra-system) | Isolation between 2 antenna ports within the same frequency band.                                                                                                                                          | dB    |
| Port-to-Port Isolation (X-band / Inter-band / Inter-system) | Isolation between 2 antenna ports in a multiple band system across separate frequency bands (co-pol & x-pol port configurations).                                                                                           | dB    |
| Port-to-Port Squint                        | Measured as max angular deviation between overlay of AZ patterns for 2 ports of a x-pol antenna - mechanical boresight required for a single port, all other ports measured from same mechanical boresight. | degrees |
| Port-to-Port Tracking                      | Measured at max magnitude deviation over the defined sector (adjusted for azimuth pan angle offset) of AZ pattern overlay for 2 ports of a x-pol antenna - mechanical boresight required for a single port, all other ports measured from same mechanical boresight where the sector is defined as follows:  
* For a nominal Azimuth Beamwidth of 45deg or Narrower (i.e. 33/45), a 60deg sector is defined (-30/+30deg sector).  
* For a nominal Azimuth Beamwidth Wider than 45deg (i.e. 65/85), a 120deg sector is defined (-60/+60deg sector). | dB    |
<p>| Power Handling (per port)                  | Max CW Power Level per single port input specified at an ambient room temperature of 20°C enduring a continuous 1 hour power soak.                                                                     | Watts  |
| Power Handling (total power)               | Max CW Power Level split equally into two ports of a dual-pol antenna (same antenna system) specified at an ambient room temperature of 20°C enduring a continuous 1 hour power soak.                                   | Watts  |
| Power Handling at Elevated Temp (per port) | Max CW Power Level per single port input specified at an ambient temperature of 46°C Celsius enduring a continuous 1 hour power soak.                                                               | Watts  |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Handling at Elevated Temp (total power)</td>
<td>Max CW Power Level split equally into two ports of a dual-pol antenna (same antenna system) specified at an ambient temperature of 46°C Celsius enduring a continuous 1 hour power soak.</td>
<td>Watts</td>
</tr>
<tr>
<td>Power Handling at Max Operating Temp (total power)</td>
<td>Max CW Power Level split equally into two ports of a dual-pol antenna (same antenna system) specified at a maximum operating temperature of 65°C Celsius enduring a continuous 1 hour power soak.</td>
<td>Watts</td>
</tr>
<tr>
<td>RAZ</td>
<td>Remote AZimuth control.</td>
<td></td>
</tr>
<tr>
<td>RET</td>
<td>Remote Electrical Tilt.</td>
<td>° downtilt (positive down)</td>
</tr>
<tr>
<td>Return Loss</td>
<td>Listed Spec; Production Spec = Listed Spec + 0.5dB margin safety factor.</td>
<td>dB</td>
</tr>
<tr>
<td>Tilt Accuracy</td>
<td>Defined as the accuracy of a given beam tilt angle per the specified downtilt of the antenna - for variable tilt, referenced to the tilt indicator defined by the label.</td>
<td>degrees</td>
</tr>
<tr>
<td>ULA Uniform Linear Array Antennas</td>
<td>Family of uniform linear array antenna configurations such as those resulting from all elements being uniformly closely spaced. E.g. ULA-2V has two columns of vertically polarized antenna elements.</td>
<td></td>
</tr>
<tr>
<td>Upper Sidelobe Suppression (USLS)</td>
<td>Level of the highest sidelobe within the first 20deg of the upper half space of the elevation pattern above horizon relative to the main beam peak level.</td>
<td>dB</td>
</tr>
<tr>
<td>X-pol Level</td>
<td>Relative level of x-pol referenced to co-pol beam maximum defined at a given angle.</td>
<td>dB</td>
</tr>
</tbody>
</table>
| X-pol Level (over Sector)                      | Maximum level of x-pol referenced to co-pol beam maximum over the defined sector (adjusted for azimuth pan angle offset) for a given port where the sector is defined as follows:  
* For a nominal Azimuth Beamwidth of 45deg or Narrower (i.e. 33/45), a 60deg sector is defined (-30/+30deg sector).  
* For a nominal Azimuth Beamwidth Wider than 45deg (i.e. 65/85), a 120deg sector is defined (-60/+60deg sector). | dB   |
| X-pol Ratio (Discrimination) on Bore sight     | Discrimination between co-pol & x-pol AZ pattern levels at mechanical boresight (adjusted for azimuth pan angle offset) for a given port.                                                                 | dB   |
| X-pol Ratio (Discrimination) over Sector       | Discrimination between co-pol & x-pol AZ pattern levels at all angles over the defined sector (adjusted for azimuth pan angle offset) for a given port where the sector is defined as follows:  
* For a nominal Azimuth Beamwidth of 45deg or Narrower (i.e. 33/45), a 60deg sector is defined (-30/+30deg sector).  
* For a nominal Azimuth Beamwidth Wider than 45deg (i.e. 65/85), a 120deg sector is defined (-60/+60deg sector). | dB   |
REFERENCES


2 “MIMO and Smart Antennas for 3G and 4G Wireless Systems – Practical Aspects and their Deployment,” April 19, 2010 3GAmericas whitepaper available on-line at: http://www.3gamericas.org/documents/mimo_and_smart_antennas_for_3g_and_4g_wireless_systems_May%202010%20Final.pdf


Section 7.1 of 3GPP Section 7.1 of TS 36.101 V8.7 states: "The requirements in Section 7 assume that the receiver is equipped with two Rx port as a baseline. Requirements for 4 ports are FFS. With the exception of clause 7.9 all requirements shall be verified by using both (all) antenna ports simultaneously." Available on line at: http://www.3gpp.org/ftp/Specs/html-info/36101.htm last accessed on April 18, 2010.


57 http://www.2comu.com/

58 http://www.feko.info/

59 http://www.ist-winner.org/3gpp_scm.html


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